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HIGH SPEED LASER WELDING
INSTABILITY AND OPTIMIZATION

By

M. Nasim Uddin

A Dissertation
Submitted to the Faculty of Graduate Studies and Research
Through the Engineering Materials Program in the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy at the
University of Windsor

Windsor, Ontario, Canada
November, 1994
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ABSTRACT

Laser welding has firmly entrenched itself as an attractive manufacturing process technology in the industry. Despite its role of a viable manufacturing process, its overall efficiency is not significantly higher than other joining processes, in particular resistance welding. It is apparent that the high traverse speed of laser welding would increase the manufacturing process efficiency and productivity.

One aspect of the research is to optimize process parameters for the physical performance of automotive body-in-white sheet steels joined by high speed welding. For this purpose, exploratory phases of pre-design experiments, bead-on-plate welding and optimization of welding in butt joint configurations are adopted.

Parameteric design schemes are undertaken in this research. The parametric design methodology is adopted to optimize the product and process design prior to recommendation for production implementation. This methodology takes into account the quality in the experimentation phase since so-called real-time quality control and/or SPC (statistical process control) can never fully compensate for all the physical process variables. Taguchi methodology, though used for other joining processes, is applicable to laser welding but has never been studied. This research discusses the laser welding optimization using Taguchi methodology. The Taguchi methodology employed a set of orthogonal arrays. The orthogonal array used in this experiment is $L_8 \ (2^7)$ orthogonal array. The $L_8$ orthogonal array employs only 8 prototype trials while the equivalent conventional full factorial experiment would be 128. Though the designs sacrifice the
effects of complex interactions of process variables, but the number of tests has been reduced 16-fold. The two levels of process variables such as speed, shield gas, flow rate, nozzle diameter are used along with three beam parameters each also at two-level. Two material conditions are also studied. The welding experiments were conducted on sheet steels in the butt joint configurations. A 10 kW fast axial flow continuous-wave CO$_2$ laser was used for all the trials. The sheets were butt welded transverse to the joint and parallel to the sheet rolling direction. The bead profile of the laser welds were investigated through visual and optical examinations. The most significant process parameters that provided the highest quality of welds were established. The quality characteristics were determined through destructive testing.

It is observed that the high speed laser welds are associated with defects such as bead protrusion commonly known as humping, hole formation, undercutting, etc. Though these phenomena have been observed previously, in high speed laser, electron beam and arc welding, there is a scarcity of reported physical explanation of the cause of these high speed weld nonlinearities. A mathematical model is developed to correlate the instabilities of high speed weld melt pool. The weld molten pool behavior is explained in terms incompressible Newtonian fluid flow. The continuity and momentum equations are formulated for surface perurbation or instability of the melt. The surface perturbation is defined as the quasi-periodic protruded bead structure measured after solidification.

The surface perturbation is not measurable within the weld speed that does not create weld defects and is distinctive of striations. The onset of instability is determined
employing dynamic similitude that correlates the weld penetration and weld speed.

A comparison of experimental welding speed showed a good approximation to the weld surface perturbation. This thesis detailed the mathematical formulation of propagation of the perturbation on the melt at high weld speed and experimentally determines the stability/instability criteria.
DEDICATION

To my family, Janet, Tarek and Rafiq.
ACKNOWLEDGEMENTS

I would like to express my sincerest thanks and gratitude to Professor Daniel F. Watt for his unparalleled guidance, supervision and encouragement throughout this research project. It was with his special skills and personal touch that I learned how engineers fix things and that it can be fun.

Special thanks to Dr. C. Zhang for her review and comments on fluid dynamic equations that are developed in this research.

I also greatly benefitted from the help of Messrs. Ruppert Corriveau, who did the metallography shown in Section 10.5.1, John Robinson and Robert Tattersall, who performed the fatigue tests.

I would also like to thank Dr. C. Schneider and Dr. W. Prange of Thyssen Stahl AG, Duisburg, Germany, for their support of this project.

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CHAPTER 1
INTRODUCTION

1.1 PROBLEM STATEMENT

1.1.1. The Automotive Body-in-white

The Automotive body-in-white is the basic structure of an automobile which bears the responsibilities of structural integrity, crashworthiness and durability. The automobile vehicle body is a product of cross-functional engineering discipline and challenges. The area of automobile body-in-white research and development is very extensive and covers all areas of science and engineering, in particular materials, materials processing and manufacturing. The material, design and manufacturing processes account for more than 85% of the body-in-white cost.

The critical factor to produce a high quality body-in-white with lower cost is to optimize material usage and manufacturing processes. The individual part manufacturing and sequential assembly processes result in lower material yield and poor quality sub-assembly.

The multiplicity of parts, processes and manufacturing systems are major problems that need to be studied. Laser welding process optimization as it relates to body-in-white materials is the purpose of this research. Laser welding is used to butt weld sheet steels of different physio-chemical properties commonly known as "tailored welded blanks" or "tailored blanks". There is very little information on these subjects in the literature, due to the proprietary and complex nature of the subject matter. Body-in-white material and process optimization requires knowledge of materials, manufacturing processes and
performance of the product itself. Very few individuals and organizations are capable of bringing together all these areas of expertise. Presently, the process tool and equipment manufacturers also lack the knowledge-base and expertise of materials, manufacturing processes and as well as the final product. This unique problem has forced automotive and related industries to develop their own process and product to maintain their competitive edge. The absence of cross-discipline interactions makes it extremely difficult to optimize the process and material utilization. As a result, some time process boundary is too wide or too narrow. The narrow boundary results in painful trial-and-error adjustments of process and the wider boundary does not take advantage of process capability. This research was conducted to establish the laser welding process parameters and their boundaries and study the performance criteria of butt welded materials.

1.1.2 Laser Welding

Laser welding of the automotive body-in-white sheet steel has been considered as an alternate competitive joining process in the automotive and related material industries. Though lasers have been used for body sheet metal product-welding applications since the mid and late 1980's\textsuperscript{1,2}, the recent development of high power lasers, beam manipulating systems\textsuperscript{3}, and optical components\textsuperscript{4} have made laser welding process and equipment an attractive flexible manufacturing choice for automotive, steel, fabrication-assembly systems and steel industries. Laser welding has also been considered as a cost-effective and competitive process over resistance spot or seam and MIG/TIG welding. The technological advantages of laser welding, namely that it requires non-contact, single-sided access, and its potential as a high speed process makes the laser a most attractive
replacement of the conventional body-in-white joining processes.

The laser sheet metal welding process and its physical phenomena have not been well understood qualitatively or quantitatively. In particular, for laser welding of sheet steel at high speed, the increase of productivity is a function of the speed of the process. The potentially higher welding speed will also reduce the manufacturing cost. However, high welding speed creates weld instabilities. These set an upper limit on acceptable welding speed. The instabilities of high speed laser welds have been observed by many researchers in different materials other than automotive sheet steels. Regardless of materials welded, the amount of literature in this area is very small. There is hardly any quantitative and qualitative description and/or explanation of high speed laser weld instability.

The purpose of this research is to review the causes of high speed weld instabilities and to propose both analytical and practical solutions of the problem. The physical behavior of high speed laser welded sheet steel will provide some insights of product performance.

1.2 RESEARCH OBJECTIVES

The objectives of this research are five-fold:

(a) To review and critically assess the body-in-white manufacturing processes and material usage. To identify and examine laser welding aspects to produce tailored welded optimized material sheets.

(b) To experimentally investigate the effects of process parameters on bead-on-plate
high speed laser welding and so as to optimize these parameters and to minimize related deleterious physical phenomena of instabilities or surface perturbation.

(c) To experimentally investigate high speed laser butt-joint welding parameters for body-in-white material optimization, and to characterize and quantitatively analyze the physical behavior of the welded materials.

(d) To analytically investigate and develop a theoretical model to gain insight into laser welding physical phenomena and instability.

(e) To recommend a quantitative solution to the high speed laser welding problems of automotive body-in-white sheet steels.

1.3 RESEARCH METHODS

To accomplish the objectives outlined in the previous section, the research has been conducted in four distinctive phases: (a) reviewing and analyzing body-in-white sheet steel applications and manufacturing processes, (b) experimental studies to quantify process variables, beam parameters and material characteristics, (c) conducting high speed laser welding experiments and parameter optimization including data acquisition and analysis, and (d) finally, development of quantitative and qualitative recommendations. Throughout the entire research project, active industrial collaboration from body-in-white design, materials and manufacturing experts has been solicited.

In the review and analysis phase of body-in-white sheet-metal applications and manufacturing processes, commercial production parts were laser butt-welded. Post weld materials were evaluated through mechanical and metallographic analysis. The purpose of these evaluations was to characterize post weld material conditions and their effects
on body-in-white assemblies or sub-assemblies. The investigation of material optimization employing laser welding provided the data which quantifies subsequent manufacturing processes to be adopted for post weld materials. Laser welded integrated sheet blanks can also reduce the pre- and post-assembly operations, if these blanks or integrated sheets are made into specific parts. The potential for increased material yield can also be realized through optimizing material by laser welding. The butt-joint experimentation phase also inferred that there is room for welding process improvement. There is also a need to adopt higher welding speed for further improvement of productivity and manufacturing cost. The objective of this task is finally to learn about laser welding process problems, limitations and methodologies and common practices, so as to rectify some of these problems and limitations. This has been accomplished in Chapters 3, and 5 through 7.

The current literature was surveyed to obtain supportive information on laser weld defects and high speed laser welding instabilities. Though a limited number of literature is available on observations of instability (see Chapter 9), there is no specific information and explanation found about the cause of instability and how it could be overcome without any additional hardware.

For the present study the high speed laser welding was conducted at BIAS (Bremer Institut fur Angewante Strahltechnik), Germany. Initially, high speed laser welding was conducted on bead-on-plate low carbon sheet steel. It has been experimentally observed² that laser butt-welding critically depends on joint fit-up condition. Therefore, initial high speed welding is conducted without introducing this
"joint clearance" variable. Another aspect was to observe experimentally high speed weld defects and the on-set of instability. The laser beam parameters and other welding process parameters were varied to observe different phase of instabilities and weld non-linearities. A visually good weld was achieved with high travel speed and careful optimization of both beam and process parameters.

The optimized process parameters data of butt-joint configuration were obtained utilizing some of the basic parameters of bead-on-plate welding. The added variable is the "joint clearance" or fit-up condition as the sheets are abutted prior to welding.

The parameter optimization of butt-joint welding experiments were targeted to obtain highest possible travel speed comparable to bead-on-plate welding speed. Again, visually no defect welds are taken as so called "good welds." Erichsen cup tests were performed on selected visually "good welds" in butt-joint configured specimens to establish a base-line performance criteria.

During the next phase of this research, the effect of different laser beam parameters and process parameters were experimentally investigated. Two levels of each parameter are selected to define and quantify process boundaries for laser butt-joint applications. The experimental design method adopted for this purpose is the Taguchi design of experiments. Five different welding process parameters were evaluated along with two different material conditions.

An orthogonal array was developed not only to assess the effect of process variables, but also the physical behavior of laser welds.

The remaining tasks of this research were devoted to characterization and physical
testing of the welded specimens. The characterization and testing were performed to enhance our knowledge of the physical mechanisms of high speed weld instability and affect of process variables.

The final task was to consolidate all the data and findings to recommendations. The experience and discovery in all the phases have been the basis of the conclusions and recommendations. The recommendations developed are to address practical engineering solutions to apply the laser welding process to sheet-metal applications. The analytical conclusions are given to address some of the physical mechanisms of laser welding process that encompasses stability and instability limits.

1.4 OVERVIEW OF THESIS

This thesis is written and compiled in the sequence of the research methodology. A background of body-in-white manufacturing processes and laser welding is presented first. This is followed by literature and Taguchi methodology review, a detailed plan of systematic design of experiments, experiments, results and characterization. An analytical development of fluid dynamic relations for keyhole stability and instability of surface perturbation is given which is followed by a detailed analysis of measurement data and discussion, and then recommendations are made.

Chapter 2 presents a detailed background of body-in-white manufacturing processes. A general view of design and material optimization scheme is presented to familiarize readers the impact of laser welding on body-in-white. Use of laser welding to consolidate material is discussed, and the consolidated materials impact on material yield, weight reduction, structure and manufacturing processes are highlighted.
Chapter 3 presents a literature review with an emphasis on laser welding process parameters, in particular, welding speed both low and high. The observed defects in high speed regime are described and its suppression techniques reported by previous researchers are also reviewed. A review of welding speed currently employed in various production applications is given.

Chapter 4 presents Taguchi methodology and how it can be used to optimize laser welding. At the present time, there is no reported use of Taguchi-design of experiments available for laser welding. Due to this unavailability, author did not have any opportunity to review previous work.

Chapter 5 details the plan of experiments. The experiments conducted in this research project is to serve the purpose of intellectuals and industrial implementations. The phased plan of the experiments covers pre-design phase, exploratory high speed welding on bead-on-plate and butt joint configuration, followed by Taguchi design of experiments.

Chapter 6 represents the experimental details. It presents materials, equipment and apparatus used in welding experiments. It describes experimental procedures, beam and process diagnostics equipment and methods. It also presents post weld characterization equipment and practices.

Chapter 7 presents results and characterization. The results are beam parameters and process parameters. The welding results of bead-on-plate, butt welding optimization and Taguchi experiments are presented in tabular form. The results of individual experiments are documented. Each experiment usually had multiple runs. The laser
beam parameters and results of beam diagnostics are presented in numerical and graphical form respectively. The welds are characterized through visual examination, optical microscopy and metallography. The results are described, sketched and photographed. The welds are tested destructively. The destructive tests are Erichsen cup test (ductility), tensile (static) and fatigue (dynamic or durability). The results are tabulated, photographed and also presented in graphical representations.

Chapter 8 develops an analytical expression for global equations that describe the dynamics of keyhole. The forces encountered in keyhole stability are vapor, plasma, radiation, surface tension, gravity, recoil, viscous and shield gas pressure. The combined effects of all the forces define the dynamics of the keyhole.

In Chapter 9 we develop an instability relation that only describes the molten pool of the weld and not the complex keyhole. This simplified relation describes both stability and instability criteria of laser welds through dynamic similitude such as Froude number. Further, the instability relation provides the theoretical speed of the weld.

An experimental verification is made between the instability relation and observed high speed laser weld defects. The observed defects such as surface perturbation are observed at lower speed than that of the prediction from the instability relations.

The main purpose of Chapter 10 is to relate the analysis of the Taguchi experimental results which were presented in Chapter 7. The analysis is based on the methodologies described in Chapters 4 and 5. And discuss the mathematical model developed in Chapters 8 and 9. The analysis is presented through an ANOVA Table. The percent contribution of each process variable is given in the ANOVA Table. The
results for each level of process parameter is graphed and discussed. The welds that have a comparatively lower tensile strength have been characterized further, and the cause of its poor performance is discussed. The discrepancy between the theoretical instability (developed in Chapter 8 and 9) and experimental results presented in Chapter 9 is also discussed. The reason for combining the analysis and discussions in one chapter is to establish continuity of all observations in this research. The research encompasses high speed bead-on-plate welding optimization, high speed butt welding optimization, Taguchi design of experiments and analysis, and theoretical interpretation and experimental correlation of high speed weld instability.

Chapter 11 summarizes the conclusions and recommendations that are discussed throughout the thesis. These are made within the context of achieving high speed laser welds for body-in-white sheet steels. The development of physical insights that provide confidence in high speed laser welding is presented in light of the research findings. The schemes of robust process development that enables production implementation for better quality and cost impact are presented. Specific recommendations are discussed in each of these important areas.
CHAPTER 2

LASER WELDING AND BODY-IN-WHITE MANUFACTURING PROCESSES

2.1 INTRODUCTION

The purpose of this chapter is to review body-in-white manufacturing processes as they relate to laser welding. This chapter also highlights some of the specific applications to outline the role of laser welding to produce quality parts. The body-in-white is the basic foundation of an automobile. It serves as a structural element and provides aesthetics and safety to passenger. The body-in-white consists of more than 300 parts with different thicknesses, coatings and geometries. These parts are fabricated through subsequent die operations. Each individual part has predefined physio-chemical characteristics and functionality such as stiffness, impact and natural frequency. The individual parts and components are subsequently made to a sub-assembly through joining processes. The joining processes are resistance spot welding, MIG/TIG and adhesive bonding. The welded major sub-assemblies are floor pan, body side frames, motor compartment panels, roof, and the body opening closure panels. The closure panels are doors, hood and deck-lid, and in some cases, the roof panel. A typical body-in-white and its part contents are shown in Fig. 1. After major sub-assemblies are built, they are assembled to frame a body shell without the closure panels. This framed body shell is subsequently resistance spot welded for stiffness and structural integrity. The complete body-in-white is then assembled by attaching all other closure panels. The closure panels are attached by resistance spot welding, MIG/TIG welding and also by mechanical
fasteners. The manufacturing processes for body-in-white are extremely involved and extensive, and spans from blanking steel from coils through successive stamping operations, handling, welding and quality control. The approximate cost of body-in-white is given in Fig. 2. It shows that material cost is 48% of the total body-in-white cost. Therefore, material optimization, or increased material yield, is essential to increase productivity and reduce cost. It is also evident that the manufacturing processes and steps need to be reduced to improve body-in-white quality and cost.

The purpose of integrating sheet steel blanks with laser welding is to reduce material usage, stamping operations of multiple parts, eliminate resistance spot or other kinds of welding for assembly operations.

The laser welding of flat sheets of steel will also reduce or eliminate scaling applications, which are considered to be environmentally undesirable elements of the structure. The material optimization by laser welding can offer several permutations. The choices are different material thicknesses, different physical properties (yield strength, fatigue resistance and impact), different coatings and in some cases, it could be entirely different material combinations, such as ferrous welded with non-ferrous materials. This variety of choices opens new opportunities for material optimization or new advanced materials with selective physio-chemical properties. There is no other technique or engineering discovery known that can produce material with different properties in the same sheet of material. These selective properties of materials in a single sheet blank made the laser welded blank an optimized material for body-in-white applications.

2.2 DESIGN
2.2.1 Conventional Body-in-white Design

In the conventional design of body-in-white components, each individual part is formed out of a sheet blank. The sheet blank is cut-out from a coil of steel. The cut-off options could be rectangular and/or trapezoidal shape. This limited option of flat blanks incurs a significant amount of engineering scrap. The engineering scrap is the designed-in waste of materials. This waste is a result of the shaped part over which auto manufacturers have no control. This engineered scrap could be as much as 65% of final material content of a part. Usually average engineering scrap accounts for 50% of the total material purchased for body-in-white applications. In North America, an average completed body-in-white weighs about 450 kgm., the wasted steel is then 450 kgm. also because of the engineering scrap.

The second step of the body-in-white manufacturing process is to add reinforcements to the individual components in order to achieve strength and/or to attach other components. The successive addition of reinforcements would ultimately result in major sub-assemblies such as doors or side frame. The reinforcement additions and sub-assembly build-up is accomplished by conventional welding processes. This assembling of body-in-white components is done in automotive assembly plants which could be physically located in different cities. The material handling and logistics may result in higher manufacturing cost, additional material handling would also damage some of the components and parts. The building of sub-assemblies to the complete body-in-white assembly would also increase the "stack-up" tolerances of the body-in-white assembly. The part tolerances and dimensional control for each body-in-white part could be a
monumental task for both the assembly and stamping plants of automotive industries. The dimension of these parts can vary from lot to lot and even can vary in the same lot or batch. All these dimensionally inaccurate parts result in dimensionally inaccurate sub-assembly in the completed body-in-white. The problem of uncontrolled tolerance stack-up in the body-in-white is visually poor fit and finish and increase NVH (noise-vibration-harshness) of the automobile.

2.2.2. Conventional Body-in-white - Undivided Sheet

Conventional body-in-white major sub-assembly part can also be fabricated from single large sheet blanks without the reinforcements. The single sheet blanks still need to go through conventional forming processes. The single sheet blank stamping does provide more accurate parts compared with divided type part fabrication. The stamping cost is significantly reduced because each individual part needs a set of dies. The material yield is extremely low for undivided type single sheet. The selective material use cannot be achieved through single sheet stamping. The conventional body-in-white manufacturing processes for both divided and single sheet blanks are compared in Table 1. The advantage and disadvantage of both conventional sheet blanks are also summarized in Table 1.

2.3 MATERIAL OPTIMIZATION

In both conventional manufacturing processes of divided and single part fabrication, the material flexibility of strength and composition cannot be achieved. In conventional sheet blanks, the reinforcements cannot be added prior to the stamping process. The reinforcements parts are made through the same processes of stamping
operations as individual large parts and are added to the base part by spot welding. The material optimization should achieve the following:

- **Higher material yield**
- **Reduce Weight**
- **Increase Material Options**
- **Enhancement of final part accuracy**
- **Reduction of post-selection manufacturing processes**

### 2.3.1 Higher Material Yield

Higher material yield can be achieved in two ways - first, reducing the engineered scrap and secondly, optimizing material selection according to its post-selection manufacturing processes. The post material selection manufacturing processes are stamping and assembly operations. The requirements for stamping and assembly are binder stocks and flanging and welding respectively.

### 2.3.2 Increase Material Flexibility

The selection of material according to its strength and corrosion resistance in a sub-assembly is the most desired option for body-in-white applications. An example of material flexibility is that in a door of an automobile, corrosion resistance is required below the belt-line. The material optimization would allow the use of coated materials or galvanized sheet steel below the belt-line and uncoated bare steel above. In the same door example, reinforcement is resistance spot welded to the hinge area to give added strength. Instead of welding another formed part or reinforcement, if higher strength material is already available at the hinge reinforcement area, there would be no
requirement for post fabrication addition of materials. This material flexibility would allow material optimization of a part according to its global physical requirements as well as its zonal needs. The example of vehicle door can be expanded to other sub-assemblies such as side frames, underbody and motor compartment.

2.3.3 Weight Reduction

The body-in-white material optimization would reduce weight by selective use of material grade and eliminating reinforcements. The selective grades of materials correspond to their unique properties, such as when HSLA (high strength low alloy) and low carbon steel are integrated. Both of them retain their physical properties but both of them could have the same thickness and mass. This unique material optimization does not add any weight to the part, conversely it reduces the weight. Before we eliminate reinforcement, we should know how we add reinforcement to a part of sub-assembly. Both the base part and reinforcement are manufactured from two dimensional sheet steels following subsequent stamping operations. The base part must have additional material, where the reinforcements should be placed and welded. In material optimization, the need for additional materials for reinforcement could be eliminated by direct integration of reinforcement to the base part. These processes can be explained through an example such as door, shown in Fig. 3. The door inner, where the hinge reinforcement is welded on, is manufactured out of 0.8 mm thick sheet steel, while the hinge reinforcement is stamped out of approximately 2.00 mm thick sheet steel. But there is already 0.8 mm thick material in place where hinge reinforcement should be attached. This additional 0.8 mm (where hinge reinforcement is attached) does not serve any purpose, but also has
detrimental effect of adding weight and stresses due to spot welding. Selective material integration would reduce this weight and eliminate stresses.

2.3.4 Part Accuracy/Dimensional Control

There are many variables that contribute to part variations - these are both stamping and assembly variations. Siekirk\textsuperscript{7} and Takezawa\textsuperscript{8} have classified both the stamping and assembly variations respectively. The dimension changes of the sub-assembly from the mean can occur due to the individual component variations. This dimensional inaccuracy of the part has also been observed by Plonka\textsuperscript{9}. The improvement in part variation due to less component part assembly has been accomplished by material integration. The computer simulation and experimental measurements of optimized material door dimensions are reported by Szefi and Uddin\textsuperscript{10}. The integrated material door resulted in Cpk improvements of 39\% to 192\% with respect to the original surfaces measured.

2.3.5 Reduction of Manufacturing Processes

Material optimization would integrate selective functions in a two-dimensional blank prior to the forming of the assembly or sub-assembly. These multi-function blanks would reduce the post-forming assembly and joining applications. The blanks already would have the reinforcing panels built-in, therefore, additional reinforcement part fabrication is not required. The material optimization method thus would reduce the number of stamping dies and operation as well as post forming assembly operations. The reduction of manufacturing processes are not limited to forming and joining operations
only. It also can reduce pre- and post-assembly sealing, material handling and production and manufacturing logistics and inventory.

2.4 MATERIALS OPTIMIZATION THROUGH LASER WELDED TAILORED BLANKS

2.4.1. Laser Butt Welding and Other Competitive Processes

Both the conventional stamping processes, whether it is divided or one-sheet type, have disadvantages of material optimization; in particular, when a selective portion of a sub-assembly requires physical or chemical property enhancements. Laser welding can be used to join different kinds of sheet steels and/or different kinds of materials. The joint configuration of laser welding could be both lap and butt joint configurations. For the subsequent manufacturing operational convenience, laser butt welding is preferred over laser lap welds. In addition to manufacturing complexities of lap welded flat sheets, there is a problem in the lap welding of coated sheet steels due to differential vapor pressures of coated and base materials. Therefore, the common joint configuration to optimize materials is butt-joint. But the problems associated with laser welding of butt joints are fit-up of abutted sheets and precise transverse alignment of laser beam to the seam. Therefore, high precision shearing of sheet steels is required prior to welding.

The immediate manufacturing steps after welding of the two-dimensional materials are stamping operations. The joining process must meet the characteristics of less heat input and/or less heat affected zone, joint strength and stamping survival of the weld. Above all, productivity also must be very high. All the conventional joining processes are somewhat limited to provide or fulfill all the requirements. Experimental work on the
conventional processes such as mashseam, flashbutt, MIG/TIG and electron beam has been done by several authors.\textsuperscript{11,12,13} Almost all the conventional processes were unable to meet all the requirements of material optimization. Azuma and Ikemoto\textsuperscript{4} concluded that TIG and CO$_2$ laser welding processes have the possibilities to satisfy all the requirements. They have compared the shear cut edge butt-welded specimen joined by both CO$_2$ laser welding and TIG welding methods. Their findings of a small hardened area in CO$_2$ laser welded specimens whereas the TIG welded specimens showed broader area of hardened zone and also a softened area. The hardened zone reduces the formability while the softened zone can yield at a faster rate to initiate failure (by shear). The optimum choice, therefore, is laser welding considering both the performance and productivity. The corrosion behavior of laser welded specimen has also been studied\textsuperscript{2}; it is observed that corrosion resistance is retained for laser welded galvanized sheet steels.

2.4.2 Laser Welding to Reduce Engineered Scrap

The material optimization should offer higher material yield. Currently, the designed-in engineering scrap for automotive body part is significantly higher; in some parts, it is higher than 65\%. In some cases, the scrap metal can be reclaimed to make a useful part. Such reclamation of scrap, also described as offal reclamation, discussed by Uddin\textsuperscript{14}, where it is shown that the throw-away pieces can be trimmed and laser butt-welded together. This optimized blank is then a useful material to fabricate a reinforcement anti-flutter bar for truck doors.

One of the most efficient material usage and reduction of designed-in engineering scrap is realized in the laser welding application of window frame rail\textsuperscript{15}. In conventional
blanking process, the blank of the part weighs about 29 kgm. (Fig.4) and coil usage is about 1.82 m²/part. The material optimization by laser welding scheme is shown in the Fig. 5. In the laser welded case, the unwelded blanks are cut from two different small dimension coils. Then these two blanks are laser welded. The dimension and weight of laser welded optimized blank is approximately 0.98 m²/part and 16 kgm./part respectively. This optimized blank resulted in significant cost savings.

2.4.3 Laser Welding to Optimize Structure

The laser welding to optimize structure has been reported by Roessler\textsuperscript{16} for front motor compartment rails and center pillar. In the front compartment rails, reinforcement is eliminated and replaced by 2.00 mm thick material in the high stress region (Fig. 6). The laser welded blanks in this case are used for both the left- and right-hand rails sub-assembly. The center pillar laser welding applications, the pillar has been redesigned to laser butt-weld two different thicknesses of materials. The upper part of the pillar is 1.8 mm thick and lower part 0.8 mm thick cold rolled sheet steel (Fig. 7). In the conventional processes and design, a reinforcement was spot welded to the upper part of the center pillar, where the seat belt is attached.

2.4.4 Laser Welding to Optimize Different Physio-Chemical Properties

The integrated optimized material blanks of four different chemistry and two different thicknesses were achieved in a production application of Toyota vehicle\textsuperscript{17}. The optimized blanks and subsequent processes are shown in Fig. 8. The welding length and material thicknesses and types are shown in Fig. 9. This laser welded blank is for the
side frame applications. This is the only known laser integrated material blank application that uses different properties of sheet steel. The optimized material blank has increased material yield by 25%. The tensile strength of the materials varies from 28 kg/mm² to 35 kg/mm². The coating weighs from 20 gm/m² to 60 gm/m².
CHAPTER 3
LITERATURE REVIEW

3.1 GENERAL LASER WELDING AND MATERIAL OPTIMIZATION PROBLEMS

There is a scarcity of reported articles on laser welding of body-in-white sheet steels. The review in this chapter is based on author’s background of body-in-white laser welding applications and limited reported works. The automotive body-in-white material and laser welding process optimization would enhance the productivity of body-in-white applications. Though the material optimization provided by laser welding has been explored on a trial and error basis within limited process parameters, no known methods or techniques have been developed by any prior investigators\textsuperscript{10,14,15,16} to optimize materials using high welding speed. It is also not very well researched with regard to material characteristics, in particular physical properties. The usual procedures and practices used to laser butt weld sheet metal for body components applications are:

- Selection of laser and optical beam delivery systems
- Process optimization within so-called window of parameters
- Material selection

The post process investigation of welded materials has been done mainly to characterize formability, because the welded material is used for three-dimensional body-in-white components. In addition, the following are also required to optimize welded materials:
- Low heat input/heat affected zone
- Joint strength same or better than that of base metal
- Formability characteristics is not seriously degraded because of welding
- High productivity both in welding speed and weld penetration.

The iteration of process variables such as both dependent and independent parameters are made following previous experience and trends. The independent variables for laser butt joint configuration are:

- Raw Beam Diameter
- Beam Focus Diameter
- Absorptivity
- Welding Speed
- Depth of Focus
- Shield Gas
- Butt Tolerance
- Edges of Sheets
- Material Specifications

After the adjustments of individual independent parameters for specific applications, and making subjective visual evaluations of the so-called good welds, the dependent parameters listed below are characterized. This characterization is for specific material combinations, which are chosen from conventional divided and/or single sheet materials and reinforcements combination sub-assemblies. The dependent variables characterized are
Weld Penetration

Hardness

Heat Affected Zone

Sheet Position Mis-match

Formability

Tensile Strength

Fatigue

The reiteration of independent variables continues till the satisfactory results of dependent variables are achieved. Most of these studies preclude the dynamic behavior of welds (fatigue) because of time and cost involved in characterizing this physical behavior. Therefore, optimized laser welded materials are made with larger process parameters windows to be "robust." The laser integrated material, being a relatively new product, even the "overdesigned" classification is still very subjective.

The high speed welding of sheet steel has not been realized for laser butt joint configuration. The specific problem of humping at high speed welding has been observed by a previous researcher\(^{18}\) in the high energy density beam welding. No physical mechanism for high speed welding discontinuities have been discussed. The laser integrated material has been produced within a speed limit between 3-5 m/min. due to these high speed welding non-linearities.

3.2 LASER WELDING

3.2.1 Introduction

Laser welding as a body-in-white manufacturing process has been accepted since
mid 1980's. Until now, however, in the automotive industries, laser welding of sheet metal is restricted to relatively few materials combinations and low speeds. The low speed and thin material welding is due to the limited availability of high power continuous wave (CW) lasers. The advent of high power lasers and beam delivery "systems" for production sheet metal applications has stimulated new interest in high speed welding for material productivity. The technological growth of high power CW CO₂ lasers¹⁹ and the existing limitations of conventional joining technology have brought forth new applications on the production floor. The laser welding advantages for sheet metal applications are the following:

- **Non-Contact Process**
- **Process Consistency**
- **No Filler Materials are Required**
- **Small Heat Affected Zone**
- **Potential of High Speed Processing**
- **Localized Processing Possible**
- **Intricate Manipulating of Beam is Possible**
- **A Variety of Materials And Their Combinations Can Be Welded**

These advantages are immediately realized by the automotive and material industries.²⁰,²¹ The commercially feasible laser welding applications have greatly increased in the recent years²²,²³ for body-in-white applications. The technical feasibility to further optimize materials and productivity was being researched²⁴.
3.2.2 Keyhole - Welding

In the case of conventional arc welding processes, the energy is deposited radially on the surface of the work-piece and is transported into the substrate mainly by conduction. Due to the conduction limited heat transfer mechanism, deep penetration and high welding speed are not achievable in conventional welding processes.

When a high energy density beam such as laser light-beam strikes a solid opaque material, some of the light can be absorbed. Due to this absorption, very rapid heating can occur, followed by melting, and removal of material by vaporization and finally plasma production (Fig. 10). The laser beam capability of power density more than $10^6$ Watts/cm$^2$ is the key factor to generate welds with deep penetration. The deep penetration welding mechanism is through "keyhole" phenomena.$^{25,26}$ The keyhole can be produced if a sufficiently high density beam strikes the metal target. Like most metals, sheet steel is a good conductor, but it reflects infra-red CO$_2$ light (wavelength 10.6μm) very strongly (Fig. 11).$^{27}$ This high reflectivity of the material results in a small fraction of absorption of the incident laser light. As the metal surface is heated, its reflectivity decreases due to its decreasing electrical conductivity. The metal in the liquid phase has higher resistivity than the solid, but the observed light absorption at high power density is much more (approximately 100%) than can be explained by the thermal change of resistivity. The absorption of light can increase if the impinged surface is somewhat distorted. This distortion can occur immediately after the melting (Fig. 12) begins. For a relatively short duration of beam impingement onto the work-piece, as the metal is vaporized and the surface is distorted, a deep hole can be formed (Fig. 13). This hole,
commonly described as keyhole or beam hole, acts as a blackbody and absorbs laser beam as well as propagating the energy further deeper into the material.

The laser weld keyhole is a cavity of vapor created and sustained by continuous vaporization of material by the high density laser beam. This vapor cavity is surrounded by molten metal interaced with solid walls. (Fig. 14). The molten metal flows back into the cavity as the beam progresses, resulting in an autogenous (i.e., no filter required) weld after solidification.

3.3 LASER WELDING PROCESS VARIABLES

In all practical applications, the process variables for laser welding play a dominant role in productivity of material processed. Moreover, improper use of laser parameters and process variables results in higher cost of laser welding because of defective parts. The process variables discussed and quantified in this research are for practical butt joint applications for sheet steel.

3.3.1 Laser Power

In laser welding, raw laser beam power is the most significant variable, and penetration depth of material depends on incident power density. In general, for a constant beam diameter at the focusing element, penetration increases with increasing laser beam power. For a particular material thickness, a minimum power is required to achieve penetration. Penetration usually increases linearly with incident laser power.28

3.3.2 Beam Diameter

Laser beam diameter determines the power density. The measurement of beam diameter of a high power laser beam is an extremely difficult task. There is also
controversy about what is to be quantified. In a Gaussian beam laser, an accepted
definition of beam diameter is where the power is reduced to $1/e^2$ or $1/e$ of the maximum
value. The beam diameter in the case of $1/e^2$ contains more than 86% of total beam
power, while in the case $1/e$ definition of beam diameter, the power envelope is
approximately 60%. Hence, $1/e^2$ definition of beam diameter is widely used for Gaussian
beam profiles.

In the case of laser beam with higher order Hermite polynomial mode structure
as shown in Fig. 15, a considerable fraction of the beam power will lie outside the $1/e^2$
region as previously defined. This situation will not account for most of the power
outside the defined beam diameter, in the case of beam with peaks at higher order mode.
Therefore, a definition is adopted for the strength of the field. The techniques of
measuring beam diameter are usually extremely subjective and mostly unsatisfactory. The
usual techniques are to burn the pattern in paper or acrylic. The burn patterns are
exposure time dependent.

3.3.3 Focus Spot Diameter

The diffraction limited focal spot size of a laser beam can be calculated from
diffraction theory, with no spherical aberrations.

$$d = 2.44 \frac{\lambda f}{D} (2M+1)^{1/2}$$ (3.1)
Where \( d \) is the spot diameter, \( \lambda \) the wavelength of the laser beam, \( f \) the focal length of focusing optic, \( M \) number of oscillating modes and \( D \) the diameter of the raw (unfocused) beam on the focusing element. It can be seen from the above equation that efficient welding can be achieved by small \( F \# \) (F-Number) or small \( f/D \) value, and as well as low order mode.

3.4 WELDING SPEED

In practical laser welding of sheet steel, welding speed is the most important of all the process variables. There is a continuous effort to achieve the higher welding speed to increase productivity of material processing. The correlation between penetration and welding speed has been discussed by Duley\textsuperscript{29}. The width and depth of melt zone depends on weld speed and power. Swift-Hook and Gick\textsuperscript{26} have calculated this power and velocity dependence by using a linear heat source with a penetration depth "\( a \).” In reference to Figure 16, the width of melt, \( w \) at high speed is (3.2)

\[
\bar{w} = 0.484 \frac{k}{v} \frac{P}{dkT_m} \quad (3.2)
\]

Where \( v \) is the velocity of the weld, \( P \) is the total power extending into the metal a distance \( d \), \( T_m \) is the melting temperature of the metal, \( k \) and \( \kappa \) are thermal conductivity and thermal diffusivity, respectively.

If all the parameters in Equ. (3.2) are assumed to be constant, then weld width would decrease with increasing speed.
3.4.1 Slow-speed Welding

The correlation between width-depth have been made with laser power and low welding speed by Duley. It has been shown that at low speed, the normalized maximum melt width reaches an asymptote with increasing power per unit penetration depth (Fig. 17). At relatively slow speeds, the penetration depth of laser welds becomes less due to formation of plasma, which attenuates the beam. Due to plasma heating, the heat-affected-zone also could be larger.

3.4.2 High-speed Welding

The depth of penetration for sheet metal welding application is not the area of concern. Penetration is enhanced by free surface depression of liquid. The free surface depression increases localized melting, and thus increases depth to width ratio of the weld. If the penetration of the weld does not vary, then the area of greatest concern is the generation of unique kinds of defects at high traverse speed. These high speed weld defects occur at free surfaces and are observed after solidification. The defects observed after solidification are

- Undercut
- Humping
- Irregular Bead

and sketched in Fig. 18.

As the weld speed increases, the instability of weld pool rapidly becomes worse, and holes are observed in the bead. A number of authors have made reference to high-speed welding defects for gas tungsten arc welding. Arata has also observed these
high-speed weld defects and suggested the use of tandem electron beams to suppress these defects. This tandem electron beam technique employs two beams of differential energy densities where the low energy beam trails the high energy beam. This technique successfully suppresses the undercut and humping bead. Arata's\textsuperscript{18} only observation is that the second beam or trailing beam allows extra time for the liquid metal to wet and fill the side walls created by the leading higher energy beam.

Steen and Eboo\textsuperscript{32} reported arc-augmented laser welding and showed that arc-supported laser process can be used to suppress some of the high speed defects. None of these authors\textsuperscript{5,18,30,31} gave any explanation of these observed defects or of how some of the techniques\textsuperscript{18,31} suppress these defects.

3.5 STATE-OF-THE-ART SHEET METAL LASER WELDING REVIEW

In order to achieve high production rates and lower costs per part, high welding speeds are required for sheet metal applications. Because of the proprietary nature of the research, hardly any information about high speed welding is available in the open literature. The welding speed as a function of sheet thickness has been reported by Prange\textsuperscript{2}, et al. Welding speeds of more than 3m/min for sheet thickness approximately 1.0 mm have been reported earlier\textsuperscript{2}. Figure 19 shows this earlier result. Recently, laser welding speed of 6 m/min has been achieved for production butt joint configured sheet steel welding\textsuperscript{33}. In all these welding applications, the maximum laser power is 5 kW. The joint clearance and presentation in relation to the incident laser beam is a major challenge for high speed welding. The relation between joint clearance and welding speed has been reported by Azuma and Ikemoto.\textsuperscript{6} In their investigation, they found that
the increasing welding speed and joint clearance would result in decrease of the thickness ratio as shown in Figure 20. The thickness ratio \( t/t_0 \) is defined by the ratio of weld thickness measured at the point of inflection of the weld cross-section and the bottom of the weld to thickness of material (Fig. 21).

Their experimental results further showed that the strength ratio, \( S/S_0 \) where \( S \) is the strength of welded sheet metal and \( S_0 \) is strength of unwelded sheet metal, decreases as thickness ratio decreases. The significance of these observations is that they determine the strength of the weld in relation to the base sheet steel. When \( t/t_0 \) is equal or greater than 0.7, the failure occurs in the base material; otherwise failure would occur in the weld (Fig. 22). Natsumi et al\(^{17} \) showed that the thickness ratio is also the determining factor for the strain limit of the welded sheet steel (Fig. 23). As discussed earlier, the welded sheet steel would go through subsequent forming operations. It is inferred by Azuma and Natsumi et al that deformation strain limit decreases sharply when thickness ratio is less than 0.7. Therefore, it is suggested that thickness ratio be maintained 0.8 or better for practical integrated sheet steel welded applications.
CHAPTER 4

TAGUCHI EXPERIMENTS - LASER WELDING OPTIMIZATION

4.1 INTRODUCTION

In this chapter a review of Taguchi experiments and how it can be adopted for general laser welding optimization is discussed. Robust process technology development is a revolutionary approach recently adopted by progressive industries worldwide. The design of experimental procedures are intended to produce required results with fewer experimental runs. Design of experiments (DOE) is a definite substitute for the "one-trial-at-a-time" method of process optimization. "Designed" experiments give accurate results at lower cost within a shorter time. Other advantages of a designed experiment over traditional approaches are the following:

- Eliminate confusing effects of two or more variables
- Establish cause-and-effect relationship among variables and their contributions to the final outcome
- Isolate random variables
- Evaluate interactions of two or more variables.

4.1.1 Definition of Design of Experiments (DOE)

Design of experiments is a tool that allows concurrent "changes" of a number of parameters, following a predetermined plan (through the use of factorial design), to study the effects of these parameters on the outcome of a process or product. A full factorial is all combinations of the experimental factors. In factorial design the rows are
experiments, columns are process variables. The number in column is setting or "level" (high or low) of the process variable.

4.1.2 Conventional DOE

The conventional DOE uses the fractional factorial designs. The conventional DOE is an improvement over the full factorial design. The full factorial design encompasses the effects of all factors or parameters while the conventional DOE is a sub-set of full factorial design. This sub-set usually allows the main effects and two-factor interactions. The usefulness of fractional factorial is to save experimental time, and still to explore the main effects and interactions.

4.2 TAGUCHI-DESIGN OF EXPERIMENTS

Genichi Taguchi\textsuperscript{34,35,36} introduced a clearly organized step-by-step approach which employs standardized orthogonal array and linear graphs to aid "designed experiments." Taguchi's linear graphs are a combination of nodes and lines used to take into account the interaction between factors and then assign all factors and interactions to Taguchi's orthogonal array. Linear graphs will not be discussed in our investigation. Interested readers may consult reference 37.

In our investigations, we have employed a Taguchi orthogonal array. A detailed description of orthogonality and the experimental matrix will be discussed in the later sections of this chapter. It is very important to mention that Taguchi's approach differentiates between controllable variables and noise factors, and treats each type of factor differently in his experiments. The conventional design of experiment does not typically make this sort of distinction. In our investigation, we have not considered noise
factors.

4.2.1 Taguchi Array

There are many Taguchi arrays, and choice of specific arrays are based on the number of controllable and noise factors. An array is also chosen based on the number of levels of each factor, and the number of factors (process variables) to be examined.

4.3 ORTHOGONAL ARRAYS

Historically, orthogonal arrays were known as magic squares. In our study, the \( L_n(2^7) \) array has been used for layouts and data analysis. In an orthogonal array, the collective low levels of any given parameter (factor) will have the same number of high and low levels of each of the other factors at the high level of the given parameter. This effectively randomizes the effects of the other parameters in terms of their effects on the high and the low level sum of the attributes for the reference given parameter. Orthogonal arrays represent a set of orthogonal linear equations.

4.3.1 Definition of Orthogonality

A linear equation with constant co-efficients \( a_1, a_2 \ldots, a_n \) can be expressed as

\[
y = a_1x_1 + a_2x_2 + \ldots + a_nx_n
\]

where the sum of the coefficients is equal to zero, i.e.,

\[
a_1+a_2+ \ldots +a_n = 0
\]

If we have two linear equations, such as:

\[
y_1 = a_1x_1 + a_2x_2 + \ldots + a_nx_n
\]

\[
y_2 = a_1^1x_1 + a_2^1x_2 + \ldots + a_n^1x_n
\]

and the sum of the products of corresponding coefficients is also equal to zero,
\[ a_1 a_1 + a_2 a_2 + \ldots + a_n a_n = 0 \]  \hspace{1cm} (4.5)

the equations \( y_1 \) and \( y_2 \) are orthogonal.

The columns of the orthogonal array in Table 2 can form linear equations in \( y_1, y_2, y_3 \ldots y_6 \) where the \( a_i \)'s = 1.0 and the signs of \( a_i \)'s are the elements of the array.

The orthogonal array in the Table 2 is an \( L_9(2^7) \). We will use \( L_9 \) orthogonal array as an example to clarify the concept of orthogonality. Usually, orthogonal arrays are constructed with symbols "-" and "+" instead of the number "1" and "2".

If we take column 1 of Table 2, the signs of experimental runs 1, 2, 3, 4, 6, 7 and 8 are -, -, -, +, +, + and +, then the coefficients \( a_1, a_2, \ldots a_8 \) of these eight experimental runs are -1, -1, -1, -1, +1, +1, +1 and +1. The linear equation of \( A \), or Column 1, can be expressed as:

\[ Y_A = -x_1 -x_2 -x_3 -x_4 +x_5 +x_6 +x_7 +x_8 \]  \hspace{1cm} (4.6)

Similarly, the linear equations of \( B, C \ldots G \) or the Columns 2, 3 \ldots 7 are

\[ Y_B = -x_1 -x_2 +x_3 +x_4 -x_5 -x_6 +x_7 +x_8 \]  \hspace{1cm} (4.7)

\[ Y_C = -x_1 -x_2 +x_3 +x_4 +x_5 +x_6 -x_7 -x_8 \]  \hspace{1cm} (4.8)

Finally,

\[ Y_G = -x_1 +x_2 +x_3 -x_4 +x_5 -x_6 -x_7 -x_8 \]  \hspace{1cm} (4.9)

Now, the orthogonality of \( Y_A \) and \( Y_B \) can be verified if sum of the products of corresponding coefficients are equal to zero. Therefore, the orthogonality relationship

\[-(1)(-1) + (-1)(-1) + (-1)(+1) + (-1)(+1) +
+(1)(-1) + (+1)(-1) + (+1)(+1) + (+1)(+1) = 0 \]  \hspace{1cm} (4.10)

is verified.
The orthogonality of $Y_A$ and $Y_C$, and $Y_B$ and $Y_C$, and so on can be verified in the same way. In our design of experiments, we have used numbers instead of signs because it will eliminate the confusion of beam focus position which is defined as (+) positive and (-) negative.

4.4 TAGUCHI APPLICATIONS - LASER BUTT WELDING OPTIMIZATION

In a step-by-step procedure to develop Taguchi array, the following items need to be considered:

- The first step in designing the experiment is to define and quantify (if possible) the objective. In laser welding optimization, our objective is to produce quality welds that have physical properties such as tensile and fatigue strength comparable to the base material and to have failure occur not at the weld.

- The second step is to establish the factors which potentially affect the objective. In this study, the factors or parameters we have considered are laser beam parameters (power, beam focus positions), process parameters (welding speed, shield gas flow rate) and material parameters.

- Thirdly, the factors must be classified as either controllable or noise. The factors which can be controlled by the operator should be used.

- Fourth, the number of levels for each factor needs to be determined.

- Finally, a $L_8$ Taguchi array for the experiment can be chosen. In our case, an $L_8$ array is the most efficient design to accommodate all six factors.
4.5 ANALYSIS OF VARIANCES

The objective of an experiment is to achieve a quality characteristic of a process or product. Our quality goal is welded sheet steel blanks that meet all the physical characteristics of an automotive body-in-white part and the quality characteristic does not deviate from the target value of physical performance such as tensile or fatigue strength. In laser welding, various factors effect a targeted quality characteristic. Therefore, we use analysis of variance (ANOVA) which is a systematic and meaningful way of statistically evaluating experimental results. To accomplish the discussion of ANOVA, we will introduce concepts such as linear equations, variation and ANOVA Table. This subject will be revisited through ANOVA Table for our investigation in Chapter 10.

4.5.1 Linear Equations and Variations

The general form of linear equation is given as,

\[ Y = a_1x_1 + a_2x_2 + ... + a_nx_n \]  \hspace{1cm} (4.10)

The sum of the square of the coefficients \(a_i's\) are called the number of units, and is designated here by \(S\), and

\[ S = a_1^2 + a_2^2 + ... + a_n^2 \] \hspace{1cm} (4.11)

The number of units is used to determine the sum of square of a variation. The square of a linear equation divided by \(S\), as defined in equation (4.11) would form a variation with only one degree of freedom. This variation can be expressed as: (4.12)

\[ V_L = \frac{(a_1x_1 + a_2x_2 + ... + a_nx_n)^2}{a_1^2 + a_2^2 + ... + a_n^2} \] \hspace{1cm} (4.12)
for Df (degrees of freedom) = 1.

4.5.2 Decomposition of The Total Sum of Squares

The total sum of squares are given by,

\[ V_T = V_m + V_L + V_e \]  \hspace{1cm} (4.13)

where \( V_T \) is the total sum of the squares of the variation, \( V_m \) is the sum of the square of the mean deviation, and \( V_e \) is the error sum of squares.

4.5.3 ANOVA Table

The ANOVA Table (Table 3) contains all the results of variation, along with the percentage of contributions \( \rho(\%) \).

4.6 CALCULATION OF AVERAGE RESPONSES

Average responses for each factor are usually calculated and plotted as a graph to show their relative significance. The calculations entail the average output of each factor at each level. The difference between the average output of each factor at each of its Level-1 and Level-2 is plotted as a two point graph. In our experiments, the outputs are the tensile strengths and fatigue lives of laser butt welded specimens.

4.7 OPTIMAL LEVELS

The optimal levels are chosen from the average response plots. In our investigation, the optimal levels would be those factors and levels that produce the welded sheet steels with the highest tensile strengths and fatigue life.
CHAPTER 5
SYSTEMATIC DESIGN OF EXPERIMENTS

5.1 PRE-DESIGN PHASE

Discussions in the preceding chapter showed that the practical laser welding applications thus far achieved traverse speed not exceeding 6 m/min. To increase the welding speed more than 6 m/min. for sheet steel welding applications, rigorous trial experiments were planned. The planning of the high speed welding trials were based on accumulated experience of laser resonator and beam parameters, process parameters and material parameters of the author. To establish a systematic experimental design, some of the basic process and beam parameters are set so as to examine both the low and high speed regions. The experiments in the pre-design phase entailed welding of low carbon sheet steels. Quality evaluation of the welds involved visual and optical microscopy of weld cross-sections and mechanical testing. In this phase, the weld speed achieved was 8 m/min. Welding speed increases with increasing laser power. The influence of laser welding parameters namely, power at work-piece, focal position, shield gas speed on visually good weld bead has been characterized. These experiments were conducted to design high speed welding for both bead-on-plate welding and welding of automotive sheet steel in butt joint configuration.

Various edge conditions of abutted sheets were investigated. The edge of the sheet steel was prepared through mechanical shearing. This specially sheared edge ensures gap less than 0.08 mm during welding. This gap condition was assumed to be
consistent in all welding conditions. The welding conditions refer to both pre-design phases and this research. A carbon dioxide laser of wavelength 10.6 μm is employed in a pre-design phase. Due to its production viability, CO₂ laser of wavelength 10.6 μm is also chosen for this research, though the initial coupling of radiation on metallic surface at this mid-infrared region is extremely poor.

5.2 HIGH SPEED WELDING BEAD-ON-PLATE

The bead-on-plate welding is designed to establish baseline parameters for high speed welding of butt joint configuration. The influence of laser welding parameters on weld bead geometry for bead-on-plate welding is to be investigated, particular the weld pool characterization after solidification. The bead-on-plate welding is conducted at the high traverse speed with one material parameter and ten laser beam and process parameters.

5.2.1 Material Parameters

A bare interstitial-free (IF 18, Thyssen designated) steel of nominal thickness of 0.8 mm is used for bead-on-plate welding. The material chemical composition and mechanical properties are described in Chapter 6.

5.2.2 Effects of Process Parameters

An attempt will be made to determine the significant process parameter effects on high speed bead on plate welding. The following parameters are varied to achieve a visually good weld with full penetration:

- Laser Power at Work-piece
- Beam Focus Position
• Shield Gas Type Flow Rate
• Nozzle Standoff
• Welding Speed

All other beam and process parameters such as beam mode, F#, laser type are kept constant during the investigation.

5.3 OPTIMIZATION PROCEDURE

An eight stage procedure for optimizing laser welding is described. The procedure uses both theoretical and a design of experiments (Taguchi method) to improve on the baseline welding speed of automotive sheet steel.

1. Establish Process Efficiency Target

Determine theoretical process efficiency target for laser welded sheet materials.

2. Compute Theoretical Energy Input

Compute the theoretical energy input, based on previous laser welding experience for both bead-on-plate and butt joint configurations.

3. Conduct Experiments: Bead-on-plate

The high speed welding on bead-on-plate is conducted to understand physical effects and boundaries of laser welding process.

4. Establish Base Line Parameters for Butt Joint Configuration

Following the established parameters for the high speed welding of bead-on-plate sheet steel, establish base line parameters of butt joint configurations.

5. Select Process and Material Parameters

To determine the effects of laser, process and material parameters, the following
test parameters are considered:

- Ten laser welding beam and process parameters
- Two ratio of thickness
- Two types of sheet steel

6. Taguchi Design of Experiments

The accepted Taguchi's methodology is the use of his tabulated sets of orthogonal arrays which are a representation of particular experimental designs as discussed in Chapter 4, the Taguchi design implementation means fewer experiments.

7. Conduct Butt Welding Experiments

The welding of butt joint configuration sheet steels would be conducted according to parameters selected consistent with a Taguchi orthogonal array.

8. Verification

Once the experiments were conducted, the welded sheet steel were visually and mechanically examined to analyze the influence of process parameters.

Stages 1, 2 were established prior to this research, and steps 3, 4, 7 and 8 will be discussed in the later chapters. The optimization stages 5 and 6 are explained in the following sections.
5.4 BUTT WELDING PROCESS AND MATERIAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>No. of Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Weld Process)</td>
<td>(Settings)</td>
</tr>
<tr>
<td>A - Laser power</td>
<td>2</td>
</tr>
<tr>
<td>B - Beam focus position</td>
<td>2</td>
</tr>
<tr>
<td>C - Welding speed</td>
<td>4</td>
</tr>
<tr>
<td>D - Shield gas flow rate</td>
<td>2</td>
</tr>
<tr>
<td>E - Nozzle diameter</td>
<td>2</td>
</tr>
</tbody>
</table>

(Material condition)

| F - Dummy                   |
| G - Y material (same or different) | 2                |

Evaluation will be done on the effects of these 6 parameters on the weld profile and mechanical behavior of laser welded connections. One more parameter may be added without changing the total number of tests required.

5.5 TAGUCHI DESIGN OF EXPERIMENTS

By testing only 6 parameters, the possibility remains open of determining whether one selected pair of parameters has a strong interaction. This will be accomplished by the method in which we assign parameters to the columns in the array.

The 6 parameters will be verified in an $L_8$ Taguchi array to test the sensitivity of the tensile and fatigue life of each of these parameters. Also, the better parameter setting (high or low value) for each parameter will be indicated with respect to prolonging fatigue life and higher tensile strengths, respectively.
Three sets of tests, each set comprising 8 experimental conditions, will be required, one set for each type of reference steel. An "experimental condition" means the individual mix of parameter settings (high or low) for each of the variables (A to G, previous section) as prescribed by the Taguchi array (Table 3). For each experimental condition, 3- fatigue and 2- tensile samples are required. More fatigue samples are required because of the scatter in fatigue test lives that is always observed for "identical" fatigue samples.

Each test sample consists of two halves (X and Y) which have been laser welded together. We need 3 sets of tests to individually test for interstitial free (IF) drawing steel, special killed mild steel and combinations of those 2. Each of these will be used as the reference steel on the X side of the test samples in a given set of tests (one Taguchi array).

The thickness and the type of steel are kept fixed in the X half of a given set of tests. The purpose of this is to ensure a common datum (fatigue failure in the X half) from which we can evaluate the relative effect of the process and material parameters on fatigue life and tensile strengths. The X half may or may not be galvanized, according to the dictates of the Taguchi array.

The Y half may be the same material as X, or it may be a stronger material if it is the same thickness. This ensures that fatigue or tensile failure will occur on the X half of the sample, so that the effects of all the parameters can be sorted out. We have chosen to weld mild steel (Y) to IF (X) material. The steels chosen for use are as follows:

- The IF steel will be IF-18, lightly temper rolled
The special mild steel will be ST14

An $L_n$ Taguchi array is shown in Table 3. The columns 1 through 7 are the parameters (A through G), and the rows are the experimental conditions. Therefore, row 1 is an experimental condition, where we use laser power 1 (Parameter A, Column 1, Level 1), set at the high level of input power at beam focus condition 1 (B, 2, 1), at weld speed (C, 3, 1), shield gas flow rate 1 (D, 4, 1), nozzle nozzle diameter 1 (E, 5, 1), material Y same as X.

Clearly, this means that a careful and detailed set of procedures will be required for sample preparation. There are two material conditions: mild steel and bare IF steel. There are two thicknesses required for each of these two. For example, to get the samples for the IF material as X, 0.8 mm thick annealed non-galvanized sheet must be welded to Set 1 as follows:

- 0.8 mm bare IF steel sheet (welded to itself)
- 0.8 mm bare IF steel
- 0.8 mm mild steel sheet, bare
- 1.25 mm IF steel sheet, bare
- 1.25 mm IF steel sheet, bare
- 1.25 mm mild steel sheet, bare
- 1.25 mm mild steel sheet, bare

The factors and levels are shown in Table 5, along with material parameters.
5.6 DATA SHEETS

The data sheets for experiments are shown in Table 6. All the detailed beam and process parameters were recorded in these data sheets.
CHAPTER 6
DETAILS OF THE EXPERIMENTAL PROCEDURE

6.1 MATERIALS

A bare interstitial-free sheet steel (Thyssen designation IF 18) 0.8 mm thick was used for bead-on-plate high speed welding. In the Taguchi orthogonal array, the material used was IF 18 and a specially killed cold-rolled (Thyssen designation ST 14) plain carbon steel at thicknesses 0.8 mm and 1.25 mm. The chemical composition and mechanical properties of IF 18 and ST 14, as received sheet steels are listed in Tables 7 and 8 respectively.

6.2 EQUIPMENT AND APPARATUS

The equipment and apparatus used in this experimental study are in a laboratory environment, but readily could be retrofitted for production. Because their usage and functionalities are not proven in the industrial environment, a detailed function description of these laboratory equipments is given. The operational methods and tolerance boundaries are extremely important to classify errors and dependence of stability of emission of laser resonator on welding; in particular, at higher welding speed.

6.2.1 Laser

The specimens were welded with RS 10000 RF 10 kW CO₂ laser in the material processing laboratory of BIAS, Germany. The laser used in this experiment is radio frequency (R-F) excited (RF frequency approximately 28.5 MHz) fast axial flow Rofin-Sinar laser type RS 10000 RF. The confocal resonator geometry has a
magnification of 2. This unstable resonator provides an annular output beam. The schematic diagram of the resonator is shown in Figure 24. The radial compressors (4) deliver the laser gas with high velocity through the discharge tubes (1) and the heat exchangers (5) into the circuit. A small portion of the gas is extracted by the vacuum pumps. The same amount of fresh gas is supplied by the gas supply. The RF generator provides the electrodes (15) with high frequency AC voltage. The end mirrors (2, 12) and the folding mirrors (6, 7) characterize the optical resonator generating the laser beam (9). The scraper mirror (11) is used as output coupler of the laser beam. The beam exits, from vacuum through a ZnSe window (3). The beam diameter is approximately 46 mm. The power of the laser can be varied from 2000 watts up to a maximum 12,000 Watts. A view of laser head is shown in Figure 25. The operating specifications are given in Appendix A for the purpose of characterization of laser welds.

6.2.2 Beam Delivery Systems and Optics

The Beam Delivery System consists of a Keplerian beam expander, a focusing mirror and pressurized beam conduit for beam propagation. The Keplerian beam expander is shown in Figure 26. The focusing optics are ZnSe lens for infra-red (10.6 μm) transmission. The distance between the lenses of the Keplerian telescope is varied to get different beam size at the focusing element. The lenses of Keplerian telescope have focal lengths 200 and 300 mm respectively.

6.2.3 Motion Table and Interface

An Anorad Motion Table of dimension 600 mm x 1000 mm is used for all
experimental studies. The motion accuracy of this table is +/-0.1 mm. And maximum velocity achievable is 20 m/min. The motion table is capable of both x-y motion. The Anorad table is CNC interfaced with the laser. This interface commands the external control, provides controllable pulse interface, and analog signals. This interface also provides power ramping and diagnostic messages.

6.2.4 Welding Head

The mirror mount and nozzle assembly are the critical components of the welding head. The off-axis nozzle assembly could be adjusted to provide different stand-off between the work-piece and nozzle. The vertical axis of the welding head can be moved up and down to achieve different depths of focus. The welding head mirror mount is contact water cooled to avoid thermal lensing of the focusing mirror. The nozzle assembly tip is threaded and different diameter tips can be put in to provide different laminar flow of the gas stream as required.

6.2.5 Laser Beam Diagnostic System

The laser beam parameter is the most critical parameter in laser materials processing. To develop and evaluate material processing, laser beam diagnostic is a must. In our experiment, we used Laserscope UFF100 to measure focussed beam diameter. The laser beam was focussed by both 200 and 250 mm focussing off-axis parabolic mirrors. The Laserscope UFF100 is shown in Fig. 27. As shown in Fig. 27, the Laserscope 100 receives the laser beam (1) through a coaxial opening onto a hollow needle (4a). Laser beam entering the needle is guided to a detector on the rotational axis (4a). The laser beam is scanned normal to the beam axis. The measurements can be presented in the
form of an isometric projection of three-dimensional intensity distribution and/or a modified form of contour line representation (Fig. 28).

6.2.6 Erichsen Cup Test

The test is conducted for sheet steels for forming applications. An Erichsen cup test machine at BIAS is shown in Fig. 29. The machine is equipped with a ring clamp to hold down the specimen while a ball penetrator moves in the upward direction to deform the sheet steel. The speed of the penetrator is usually a fraction of a millimeter per second. The drop in load on the specimen is the indication of the end point of the test, indicating the specimen has failed by cracking or necking.

6.3 WELDING PROCEDURE

6.3.1 Bead-on-plate Welding

The bead-on-plate welding was conducted to explore high speed welding instabilities and to provide solution. Bead-on-plate welding is not a part of the Taguchi experiments. The bead-on-plate welding was performed on IF 18 sheet steels of thickness 0.8 mm. The work-pieces were fixed on the motion table by a manual fixture. After the sheet was clamped, the fixed laser beam was passed over the work-piece by movement of the numerically controlled motion table. The motion table was servo controlled, so the velocity was precisely controlled.

The high speed bead-on-plate welding experiment started with 10 kW power at the work piece, with focal position at the top surface of the work-piece. The initial velocity of the table was 15 m/min. The speed of the table is the welding speed. The shield gas was helium, and flow rate was 15 l/min. The shield gas nozzle diameter was
5.0 mm and projecting at 45° angle with laser beam axis. The shield gas nozzle standoff was 12.0 mm and leading. The shield gas nozzle is designed to provide plasma suppression, by forcing the plasma to be confined in the keyhole. The suppression technique is shown schematically in Fig. 30. The next experiment was performed with a higher flow rate of 25 l/min. The next five experiments were performed varying only the focal positions. The focal position is varied by adjusting the Z-axis of the welding head. The variation of focal position conventionally taken as positive is the focal position below the surface. If it is above the surface of the sheet steel, it is taken as negative. The focus position was varied from -3.0 mm (above the surface of the sheet steel) to +3.0 mm (below the surface of the sheet steel). The welding speed was reduced to 12.98 m/min. at experiment number 7. In experiments 2 through 7, the power at the work-piece was measured to be 9 kW. The power at the work-piece for high speed welding is kept constant at 9 kW from experiments 2 through 17. The adjustment of the nozzle diameter and flow of shield gas were made through experiments 8 to 16.

The gas nozzle stand-off distance was varied only 2mm from 12 mm to 10 mm by adjusting the vertical axis of the motion table. The stand-off of nozzle was at 12 mm for experiments 1 through 7 and changed for experiments 8 through 16 to 10 mm. The stand-off measurement was taken from the nozzle tip to the laser beam intersection and shield gas application point. The bead-on-plate experiments were conducted with helium shield gas only. The visually so-called good bead-on-plate welding formed the base line process parameters for the next phase of sheet steel welding of butt joint configuration.
6.3.2 Laser Butt Welding Optimization

The materials used in the butt weld optimization experiments were edge prepared employing a special shearing operation. The special shear produces higher shear-to-break ratio, approximately 2-3. The materials used in these experiments had edge condition of shear-to-break ratio of 2.33 approximately. The materials welded in these experiments were all in the as received condition. The laser butt weld experiment (Experiment #18) was conducted with process parameters developed for the "bead-on-plate" process parameters of Experiment #17. The welding speed for experiment #18 was 16.02 m/min. The butt welding experiments #18 through #21 were conducted to understand the problems of high speed laser welding of the butt joint configuration. All the burn welding parameters were unchanged during experiments #18 through #21. The experiments 22 through 24 were conducted with laser beam focussed at +3.97 mm. Experiments 25 and 26 were conducted at the same focus position as experiment 24 at welding speeds of 15 m/min. and 14.52 m/min. respectively. The power at the work-piece in experiments 27 through 30 were conducted at 10.3 kW power at work-piece with varying focal position and speed. The focal positions were varied between 3.5 mm and 4.0 mm, whereas the speeds were varied between 12 m/min. and 13 m/min. respectively.

The power at the work-piece for experiments 31 through 35 were 9.0 kW, the welding speed (13.02 m/min.) and all other process parameters were held constant with exception of focal position. The focal positions were varied from +4.0 mm with a decrement of 0.25 mm to +3.25 mm. Experiments 36 through 38 were conducted essentially at 7.5 kW power at work-piece and a welding speed of 10.98 m/min.
Experiments 39 through 50 were conducted with Argon shield gas at 20 l/min. The welding speed was reduced to 9.0 m/min. The stand-off distance of shield gas nozzle was maintained at 10 mm from the work-piece. The IF 18 material was butt joined to itself for experimental conditions 39 through 45 and, for 46 through 50, the material ST 14 was butt welded to itself. The parameters for butt welding are summarized in Table 10.

6.3.3 Laser Butt Welding Employing a Taguchi Orthogonal Array

The experimental conditions were designed following the Taguchi's orthogonal array. The experimental conditions are developed based on experiments of Section 6.3.1 and 6.3.2 and the author's experience-base developed during different phases of laser butt welding research. The Taguchi design of experiments fundamentally sacrifices information about interactions, although a very limited number of interactions were included. The experimental design purpose is to develop a proto-typing methodology, primarily involved in quantifying the sensitivity of process parameters. The experiments were conducted at two levels of power, 9.0 and 7.5 kW, at the work-piece and four different levels of welding speeds. All other process parameters were of two levels or setting. The welding speed was varied from 7 m/min. to 13 m/min. The different parametric variations are shown in Chapter 7 and data are recorded in the data sheets. The materials welded in these experiments were all uncoated. The material types were IF 18 and ST 14 of 2 different thicknesses.

6.4 EXPERIMENTAL MEASUREMENT OF BEAM AND PROCESS
PARAMETERS

The experimental measurement techniques of all laser beam parameters and process parameters are described. The beam parameters measured in these experiments are unfocused beam profiles, intensity profiles of focussed beams and power at work-piece. The beam parameters dictate power density to initiate a keyhole, melt depth and width of the weld pool.

6.4.1 Unfocused Beam

The unfocused beam profiles were measured at close proximity to the focusing mirror. The measurement position from the output coupler is approximately 13.6 meters. This position is 100 mm behind the focusing mirror. The measurements were taken by burning wood. Figures 31 and 32 show the wood burn patterns for focal lengths of 200 and 250 mm respectively.

6.4.2. Intensity Profiles

The intensity profiles around focal positions of mirrors of focal length of \( f = 200 \) mm and \( f = 250 \) mm were measured. The intensity profiles at the focal position were not measured because it exceeds the damage threshold of the measuring device. The experimental measurements were taken by Prometec laserscope UFF 100 (as shown in Fig. 27). Figures 33 through 40 show the isometric projection of the intensity distribution and contour representation of different positions parallel to the focal plane. The measurements are taken at power 9 kW and 7.5 kW, and focal lengths of 200 and 250 mm.

6.4.3 Power
The power was measured by a calorimetric device. The laser beam was incident for a fixed length of time to heat the calorimeter, the measured temperature difference is proportional to laser power. The accuracy of this measurement is within ± 2% of the measured power.

6.4.4 Welding Speed

The welding speed was controlled by the Anorad Controller. The velocity of the table was taken as the speed of the weld.

6.4.5 Shield Gas Flow

The gas flow measurement is taken by the measurement of position of a movable spherical ball in the cylindrical tube. The measurement conditions:

- Pressure: 3 bar relative to the ambient
- Temperature: 20° C

The flow rate was then calculated from Figures 41 and 44. The horizontal-axis is the scale on the tube where the ball lifts and vertical axis corresponds to the gas flow. The gas flow is indicated by the vertical axis of Figures 41 through 44 which corresponded to shield gas flow at the exit of the nozzle.

6.4.6 Other Parameters

The other parameters such as nozzle stand-off, nozzle diameters were measured with simple calipers.
CHAPTER 7
RESULTS AND CHARACTERIZATION

7.1 INTRODUCTION

In this chapter, the measured values of laser beam and process parameters are documented. In addition to the compilation of the results, some of the welded specimens are characterized both non-destructively and destructively. Some of the beam parameters terminologies are discussed in Chapter 3, and others are defined in references 38 and 39. The process parameters are also tabulated in this chapter to aid better correlation with observations and weld characterization.

7.2 BEAM PARAMETERS

The Free Propagating Beam Shape

The shape of the freely propagating beam was detected by Laserscope UFF100. The raw beam shape at different distances from the laser output coupler is shown in Figure 45 which shows the beam diameter at different position without the telescope.

Beam Waist Diameter: 19 mm

Distance between beam waist and output coupler: 8 m

Beam Quality Factor

The beam quality factor was obtained by the quantitative estimate of the mode structure by dividing the diffraction limited spot diameter by experimentally measured focus spot diameter. The fraction is defined as the beam quality factor. The beam quality factor was found to be $K = 0.15$
 Beam Profile at Near and Far Field

The beam diagnostic system used in this experiment, Prometec UFF 100, was unable to measure the beam profile at the near and far field. The burn patterns on the wood are the characteristics of beam profile (as shown in Figs. 31 and 32).

Distance between "Telescope and Output Mirror": 2.0 m Distance between "Telescope and Focusing Mirror": 13.6 m

Focal Length of Focusing Mirror: 200 mm

Laser Resonator Type: Unstable

Power Stability Δp (f<1000 Hz): +/- 20%

Power Stability Δp (f>10 Hz): +/- 5%

The Beam Shape After the Telescope

The beam shape after the telescope is shown in Figure 46 which describes the beam diameter at experimental position. The experimental position was 13.6 m.

Focus Spot Size

The focus spot size measured for 9 kW power at work-piece for focusing mirrors of focal length 250 mm and 200 mm are shown in Figures 47 and 48 respectively. The similar focused beam for 7.5 kW power at work-piece for focusing mirrors of focal length 250 mm and 200 mm are shown in Figures 49 and 50 respectively.

Focus Diameter and Telescope Adjustments

The influence of telescope adjustment Δf on focus spot size is shown in Figure 51. Δf is the distance between optics 1 and 2 of the Keplerian telescope (Fig. 26). The distance between optics 1 and 2 were adjusted to obtain the desired focal spot size that
corresponds to the free propagating beam shape of the focused beam when different focusing elements such as 250 mm and 200 mm are employed.

7.3 PROCESS PARAMETERS

The process parameters relating to high speed welding for bead-on-plate and butt welding optimization are summarized in Tables 9 and 10 respectively.

7.3.1 Bead-on-plate

The bead-on-plate welding was conducted from experiments 1 through 17 as shown in Table 9. The experimental conditions 1 and 2 employed velocity of 15 m/min. The beam focus position was placed at the surface of the sheet. The focal length of mirror was 200 mm. These high speed welding conditions resulted in an irregular bead.

These experimental conditions further resulted in bead protrusion and through thickness sheet cutting in each case of a protruded bead. These quasi uniform bead protruded profiles are shown in Figures 52 through 54. The next set of experiments (not recorded) with beam defocus 0 to ±2 mm produced an irregular bead with quasi-periodic humping and under cut. The shield gas flow rate in experiment #2 is changed to 25 l/min. with focus position still on the surface of the work-piece. There is no significant change in the bead profile as obtained in the previous experimental conditions. The non-linearities of all the bead profiles were recorded. The "protrusion" of beads were measured and listed in Table 15. The protrusion varied anywhere between 0.5588 mm to 1.397 mm in height. These variations of height were measured in two different plates marked "y" and "z". In Experiment #3, the beam was defocussed to +3 mm, and the
plasma noise was quiet. To set the boundary of "beam defocus," in Experiment #4, the beam was defocused to -3 mm. The irregular bead resulted again. In Experiment #5, the beam position was defocused to +2.5 mm, and produced a visually irregular bead without any through-cut obtained. In the Experiment #6, the defocus position was changed to +2.75 mm, a bead without any protrusion was obtained. However, periodic bead swallowing and intermittent penetration in the back side of the sheet resulted. In Experiment #7, the weld speed was 13.98 m/min., and defocus was kept at +2.75 mm, no significant change of top bead profile resulted and the bottom bead profile was pronounced. In the cases of Experiments 6 and 7, the top beads were wider and the surface characteristics were like straight rope (shown in Figure 55).

In Experiment #8, the reduced shield gas flow rate and nozzle diameter resulted in a visually similar bead profile. Experiments 9 through 15 resulted in quite similar bead top and bottom bead profile. In Experiment #16, the bottom bead showed better penetration, though the laser beam was defocused to +3.5 mm. In Experiment #17, the velocity was increased to 16.02 m/min. The bottom bead showed very good penetration.

7.3.2 Butt Welding Trials/Experiments

These welding trials were conducted to optimize high speed laser welds of butt joint configurations, the initial process parameters utilized are those of Experiment #17. In Experiment #18, a visually good weld with partial penetration was obtained. Though the same parameters were used for trials 19 through 21, the welded samples were separated and beam position was off line by 0.1 mm. The beam was centered for trial 20. For cases 20 and 21, visually good welds resulted only on approximately half of the
length sample. The others were porous, mainly due to excessive gap between the abutted sheets. In Experiment #22, the focal position was changed to +3.97 mm. Again, visually good weld over half of the entire weld length resulted. The experimental conditions gave similar results for trials 23 through 24.

In the experimental conditions of 25 and 26, the welding speed of 15m/min. and 14.52 m/min. did not result in any significant improvement of weld profile. In Experiment 27, the power at the work piece was measured to be 10.3 kW and the weld speed of 12 m/min. resulted in a good seam with visual disruption of bottom seam. This experimental condition was repeated in trial 28 with the exception that the beam was defocused to +3.5 mm (previously Experiment #27, defocus position was at +3.97 mm). In Experiment 29, the speed was increased to 13.02 m/min. In Experiment 30, the focal position was moved to +4.0 mm with no visual change in the welds.

In experiment 31, the power was measured to be 9 kW, and this was kept constant through Experiment 35. The focal position was moved with a decrement of 0.25 mm from +4.0 mm to +3.25 mm, the experimental conditions resulted in welds which were visually characterized to be good welds.

Experiments 36 through 38 were conducted at a reduced power of 7.5 kW with reduced He gas flow rate of 15 l/min and the nozzle diameter were 12 mm and 5 mm respectively. The weld for these experiments resulted in the wider bead widths.

7.4 BUTT WELD CHARACTERIZATION

A group of welded and unwelded IF18 samples were characterized prior to the two-level Taguchi experiments. The characterizations were visual inspection of the
Erichsen Cup deformation test. The purpose of the latter is to determine and compare the formability of the welded and unwelded sheet steels and to evaluate the dependence of formability on laser welding process parameters.

7.4.1 Visual

**Experiment 24**

The specimens of experiment 24 showed partial penetration with no visual disruption of the bottom bead. The top weld bead width was 1.5mm.

**Experiment 30**

The welded specimens of experiments 30 showed uniform top and non-uniform bottom beads with widths of 1.5mm and 0.5mm respectively.

**Experiment 31**

The top weld bead profiles are non-uniform in widths. The bottom bead has intermittent penetration. The top bead width varied from 1.0mm to 1.5mm. The bottom bead widths varied from 0.25mm to no penetration. The top bead profiles also showed undercuts.

**Experiment 32**

The top weld bead showed undercuts and bottom bead showed intermittent penetration with undercut. The top bead widths are about 1.0 mm and bottom bead width varied from 0.25 mm to no penetration.

**Experiment 33**

In experiment 33, a uniform top bead of width 1.25mm and bottom bead with continuous penetration is observed. The penetration did not result in severe surface
disruption. The bottom bead width is approximately 0.25mm.

7.4.2 Erichsen Cup Test

The Erichsen cup test is performed for individual sets of experiments. The cup test was performed with the penetrator centered on the bottom bead or top bead of the laser welds, designated as top and bottom displacements, respectively. Results were measured in triplicate. The cup height results are shown in Table 11. The height of the cup in millimeters at fracture is a measure of the ductility. The deformation of the welded and unwelded specimens are shown in Figures 56 through 61.

7.4.3 Metallography

Erichsen cup test specimens were examined metallographically. The results are shown in Figures 62 through 65. The cross-sections of the welds were observed under optical microscopy at 80x magnification. The samples were prepared in automatic metallographic devices with sequential steps of grinding and polishing and a final step of etching in nital solution. The cross-sections of the welds showed the penetration and widths which established a relationship with ductility.

7.5 TAGUCHI EXPERIMENTS

The results of process parameter variations for each experimental condition were evaluated by visual, optical examination and mechanical testing.

7.5.1 Process Parameters

The process parameters of Taguchi experiments are shown in Table 12. The two level process boundary is established through previously developed process parameters and characterization. The experiments are designated 1 through 8. Each of the
experimental conditions is set-up in such a way that the orthogonality of the Taguchi matrix is maintained. Visual examination of samples from each experimental group is made to establish a preliminary assessment of the welded samples.

7.5.2 Visual Characterization - Taguchi Samples

The samples were observed with an optical microscope for visual characterization of surface topography, bead profile, heat affected zone and solidification pattern. A summary of the observed characteristics for each set of test conditions is given below.

**Series 1** - Top*: Different thickness sheets were welded together, flush on the root side. The weld bead length and width were 15.5mm and 0.5mm respectively. No visual defects or under cut, defined teardrop or chevron pattern were observed. The HAZ is symmetric.

Bottom*: Full penetration was observed. Joint mismatch (means the bottom of the abutted sheets are not co-planar), bead width of 0.3mm, undercut, were also observed. The color of the bottom bead was black and brown.

*Top is designated as beam impingement side and bottom is the root side.

**Series 2** - Top: Same thickness of sheets was welded. The weld bead length and irregular bead width were 15.5mm and 0.5 - 0.75mm, respectively. No defined teardrop and asymmetric HAZ of 3.0mm width were observed.

Bottom: Intermittent root and bulging, irregular bead width 0.3mm - 0.5mm, small asymmetric HAZ were observed.

**Series 3** - Top: Different thickness of welded sheets with weld bead length of 16mm, and bead width 1.0mm were observed. Uniform bead profile, non uniform teardrop, brownish color, non uniform heat affected zone were also observed.
Bottom: There was no root (or bead) at the bottom. Non uniform heat affected zone (width of HAZ 0.25 - 0.5mm) was observed.

**Series 4 -** Top: The weld bead length of 16mm and bead width of 1.0mm were observed.

A non uniform bead profile, well defined but non uniform teardrop pattern, non uniform HAZ, brown color were also observed.

Bottom: At the bottom there was no root (or bead). There was insignificant surface disruption. The heat affected zone was 1.0mm, and showed brown color.

**Series 5 -** Top: The weld bead length and width were 15.5mm and 1.5mm, respectively.

A well defined but non-uniform teardrop, symmetric heat affected zone, silvery surface were observed.

Bottom: The bottom bead lacked full penetration. There was intermittent penetration of 1mm in length and 0.5mm width. The bottom surface showed heatmark and had visual crack line or opening. The wide non uniform heat affected zone of 2 - 2.5mm was observed.

**Series 6 -** Top: Multiple thicknesses of sheets were welded. The weld bead length was 15.5mm. The uniform weld bead width of 1.5mm with well defined teardrop and symmetric HAZ were observed.

Bottom: There was an intermittent root at the joint line. The root spacing varied from 1 to 3mm. The root length varied from 0.5 - 1.0mm, with width approximately 0.5mm. Visual surface disruption, heat affected zone of 1.0mm width were observed.

**Series 7 -** Top: The top weld bead of 15.5mm and non uniform bead width of 1.25mm - 1.5mm were observed. But yet, some surface porosity, visual teardrop without
connection, uniform HAZ of 1.0mm, with silver color were observed.

Bottom: Intermittent root and surface disruption were observed. The root width of 0.5mm, length of 0.5 - 1.0mm, and heat affected zone 1.0mm (with brown color) were observed.

**Series 8** - Top: Multiple thicknesses of sheets were welded. The weld bead length of 15.5mm, and uniform bead width of 1.25mm were observed. A well defined teardrop with sharp corner, (HAZ more in thinner section), non uniform heat affected zone, silver color were observed.

Bottom: There was no distinct root or surface disruption. The dimension of penetration mark was 0.25mm. The round shaped penetration mark was away from the weld centerline. A non uniform 2.0mm heat affected zone and brown color were observed.

**7.5.3 Optical Microscopy of Weld Profile**

**7.5.3.1 Low (12x) Magnification**

The low magnification optical microscopy of welded samples are shown in Figures 66 through 73. The entire bead length of top and bottom surfaces were photographed. The perspective view of weld profile showed full penetration for the case of experiment 1-series (Figure 66), and complete lack of penetration for the case of 5-series. From series 5 (Figure 70) picture showed the bottom crack. Insufficient or complete lack of penetration was observed in series 3, 4, 8; corresponding to Figures 68, 69 and 73 respectively. Figure 67 (series 2) shows some undercut in the bottom bead. Series 7 (Figure 72) showed uniform top bead and intermittent penetration in the bottom bead.
7.5.3.2 **Higher (39x) Magnification**

The high magnification weld profiles are shown in Figures 74 through 79. Optical microscopy showed the surface structure (post solidification structure) at different processing conditions. The surface profiles varied from well defined teardrop or chevron pattern to the transition to unconnected teardrop. In the case of high welding speed (Figure 74), there was no teardrop observed. In Figure 74 (series 1), wavy patterns were observed along the walls of the weld bead. Slight bulging in the bead profiles were also observed. Figure 75 (series 2) showed Chevron patterns with long connected lines, while the bottom side showed an intermittent Chevron pattern. Figure 76 showed a Chevron pattern with elliptical shape while the bottom did not show any pattern due to lack of penetration. Similar trends were observed in Figure 77 for the experimental series 4. A larger pattern with non uniform bead profile was observed for series 5, while the bottom part showed only the heat mark a with distinctive crack. Figure 78 showed intermittent penetration at bottom bead. Figure 79 showed structure similar to series 1 with exception that the bottom bead has intermittent penetration. Figure 79 (series 8) had the surface structure of pointed tear drop, which met at a certain characteristic angle.

7.6 **TENSILE TESTING**

Tensile tests on the unwelded IF 18 and the welded series 1 through 8 were conducted on a digitized screw-driven Instron (model TTD 30-20) tensile testing machine of load capacity of 44,100 kgm. The dimensions of tensile sample are shown in Figure 80. The samples were tested in the as-received laboratory and under ambient conditions. The tensile test results have been summarized in the last column of Table 4. Figures 81
through 89 show the load vs. displacement plots of unwelded and welded samples of series 1 through 8. The series 1, 6 and 7 test samples failed in the base material while the others failed at the welds.

7.7 FATIGUE TESTING

The fatigue test samples were fabricated as shown in Figure 80. The laser butt weld was emplaced from one end to the other of the two abutted pieces. The ends were hand filed to make thickness sides square, and free from the burr created when the samples were sheared. The specimens were gripped in self-aligning hydraulic grips and then cycled in an Instron Servo-hydraulic universal test machine under ambient laboratory conditions. Both unwelded IF 18 and welded specimens of Series 1 through 8 were cycled from zero to a common, predetermined tensile load \( R = 0 \), where \( R = \text{min.}/\text{max. load} \). The loads of the fatigue tests were determined through the tensile testing of both the welded and unwelded specimens. All fatigue tests were conducted at a frequency of 30 hz. The tests were terminated when specimen separation resulted, whether through weld bead or at the base material failure, or when the number of cycles exceeded 5 million. Fatigue results were summarized in Tables 13 and 14 for unwelded and welded samples, respectively.
CHAPTER 8

ASPECTS OF HYDRODYNAMICS OF LASER WELDING

8.1 INTRODUCTION

In the deep penetration mode of laser welding, a hole is formed which is commonly known as keyhole. The molten metal is transferred from the front wall of the keyhole to the trailing edge by the fluid flow. The flow of the metal from the trailing molten pool into the previously occupied moving keyhole should result in an autogenous weld. As the beam moves relative to the workpiece, advancing the keyhole through the metal, there is also some material loss due to vaporization. The cross-section of the molten material around the keyhole was assumed to be nearly circular as suggested by Klemens, though its diameter in the penetration depth is not independent. Klemens discussed the problem of cavity formation and depth but without any detailed considerations of flow of material in the cavity or the trailing edge of molten pool. Chan, et al., discussed the role of convection in the melt pool and disregarded all surface perturbations and other transport phenomena. The role of plasma absorption in laser welding within and above the keyhole would determine the welding efficiency. The effects of plasma at different intensity thresholds have been described by Beyer et al.

The strong dominance of polarization effects at low welding speed was observed, and as the welding speed is increased polarization effects are no longer sustained. Though Beyer accounted for plasma effects, he did not explain the behavior of the melt pool at different intensity thresholds and ignores plasma effects at higher power and speed.
The surface tension gradient driven flow has been identified as one of the major forces that acts to obliterate the keyhole. In addition, surface tension gradient driven flow creates surface striations and is responsible for convection in the melt pool. The physical phenomena of all transport mechanisms and their causes have been investigated and explained individually. Some of the major physical phenomena will be discussed concurrently in this chapter, and major forces on a fluid element in motion will be discussed. The governing equation of motion on the fluid element will be developed.

8.2 STABILITY AND COLLAPSE OF KEYHOLE

As discussed in section 3.2.2, the actual welding occurs only in the solidified melt pool trailing the keyhole. The keyhole, formed as the beam or part is moved at a certain or constant velocity, can be described as an stabilized condition. Otherwise, for a stationary beam and zero velocity part, the keyhole should theoretically grow indefinitely and unsteady state condition will result. But a stable steady state can only occur within a window of process parameters such as power, speed, focussed beam radius and suppression techniques of plasma. A few analytical models of heat and motion of the weld pool in keyhole welding with continuous wave CO₂ lasers have been reported.⁴³,⁴⁴

We shall discuss the analytical treatment of Klemens⁴⁰ that illustrates some important features of the cavity and its surroundings. Klemens considered the flow conditions in the horizontal plane with fluid thicknesses of \( t_f \) and \( t_s \) in the forward and side respectively. Due to the symmetry, he modelled only one quadrant of keyhole and its surroundings, and proposed quantitative relation of melt front thickness, \( t_f \) for keyhole speed of \( v_o \).
\[ t = \frac{\alpha_{L}}{v_{o}} \frac{T_{v} - T_{m}}{T_{v} + H_{m} / C} \quad (8.1) \]

Where \( \alpha_{L} \) is the thermal diffusivity and \( H_{m} \) latent heat of melting per unit volume with specific heat \( C \), the temperatures of the phase boundaries are vaporization and melting temperatures, \( T_{v} \) and \( T_{m} \) of the material respectively. The melt front is squeezed to flow around the keyhole by the evaporation pressure at the front wall of the cavity. Klemens suggested that a fraction \( \beta \) of material be transported across the cavity as vapor to stabilize the keyhole, hence

\[ \rho_\nu \ v_\nu = \beta \rho_o \ v_o \quad (8.2) \]

Where \( \rho_\nu \) is vapor density and \( v_\nu \) is the speed of vapor flow, and \( \rho_o \) is density of solid and liquid assumed to be the same.

The flow of vapor from the front wall of the cavity creates an excess pressure via momentum transfer. This pressure \( P \), is given by

\[ P = (\beta \ \rho_\nu \ v_\nu) \ v_\nu \quad (8.3) \]

The liquid adjacent to the front wall must gain flow velocity \( v_o \) from this pressure, hence (8.4)

\[ P = \frac{1}{2} \rho_\nu v^2 \quad (8.4) \]

The liquid flow around the cavity per unit time and unit cavity length, \( v_L \), is a fraction of \((1-\beta)\) of the total volume, \( v_o r_o \), swept out by the half keyhole, where the keyhole radius is \( r_o \), combining all the above equations yields (8.5):

\[ \beta = \left( \frac{r_o v_o}{\alpha_{L}} \right) \left( \frac{\rho_o}{2 \rho_g} \right)^{1/2} (T_{v} + H_{m} / C) \ (T_{v} - T_{m})^{-1} \quad (8.5) \]
Since $\rho_2/\rho_1 = 10^4$ and $\beta$ is small. Though Klemens' treatment provides some quantitative insights into the process, in reality physical phenomena during high-power laser keyhole welding is quite complex. The pressure inside the cavity is a function of keyhole geometry, thus

$$P = P(x,y,z) \quad (8.6)$$

Also, the cavity shape is not cylindrical, but rather cone-like and constricted due to local breakdown of front wall as beam propagates down the front wall. Furthermore, the plasma inside the keyhole becomes absorbing as the power increases. This, along with increasing $\beta$, results in saturation of keyhole depth.

For sufficiently high speed, the absorbing mechanism in the keyhole also changes from the inverse Bremsstrahlung absorption to Fresnel absorption. Therefore, the keyhole profile becomes more tapered in shape as the translation speed increases. It is shown numerically by DuCharme, et al\textsuperscript{19} that the collapse time of keyhole decreases as the weld speed increases. It is shown that the approximate cylindrical shape of the keyhole at lower speed has longer collapse time compared to taper shape keyhole at high speed (which has shorter collapse time after the extinction of laser beam).

### 8.3 LASER WELDING - PHYSICAL BASIS

Some of the steps of basic material interactions in laser welding and formation of keyhole are sketched in Figure 90. The energy loss mechanisms in each stage of interaction are also identified. Initially laser radiation is absorbed by the metal. Metal
being a specular surface, most of the CO₂ laser radiation of wavelength 10.6 μm incident on to the workpiece reflected. The absorption of the laser beam on the other hand depends on surface condition such as roughness, oxide layer, cleanliness, etc. The non-reflected beam energy heats the metal. As the temperature of the substrate increases, the fraction of laser beam absorbed also increases and further melting occurs due to continuous heating, and melt is also depressed further. The surface tension driven flow is generated, and as a result of further heating, vaporization occurs. The surface tension gradient driven flow and recoil pressure of evaporating material act to cause the melt to move away from the beam path. These material removal and severe melt depression result in the hole as commonly described as "keyhole" or "beam hole." The keyhole is initially filled with vapor and further interaction with laser beam produces plasma. The plasma radiates and also absorbs the incoming laser beam. The actual welding occurs when the melt pool trailing the keyhole fills the hole and solidifies. The keyhole formed by the constant beam traverse speed can be considered as a keyhole at steady-state. If the workpiece were stationary with respect to the immobile incident beam, then, theoretically, the keyhole should grow indefinitely or at least so large that very little energy could be transferred to the keyhole walls. The steady-state for a moving keyhole can only be achieved within certain windows of process parameters. The steady-state condition weld will occur without any defects, such as undercutting, humping bead, and porosity, etc.

The dominant physical mechanisms of laser welding in keyhole mode are absorption, melting, vaporization and plasma production. While the energy losses
associated with keyhole welding are reflection, material loss by evaporation and melt displacement. The transition of target temperature rising to the melting point of substrate is very important in welding, because of the significant change of optical characteristics of the surface.

Complex mechanisms arise as the boiling point of the substrate is reached. At high power density the evaporation rate is high in the initial stages, but as the vapor density increases, the incident beam is readily absorbed in the region of vapor-filled keyhole. The vaporization of material is pressure dependent, the radiation pressure due to the focussed laser beam absorbed is significant and would play an important role in the vaporization. The escaping particle would also exert pressure on the surface of the melt.

In welding the absorption phenomena are complicated by the plasma formation and suppression techniques. The suppression techniques disperse the plasma from the beam path and may also confine the plasma to the keyhole. The plasma density most likely be non-uniform inside the keyhole and may vary with the depth of the cavity. The incoming radiation in the cavity is absorbed in the cavity resulting in further heating. (The incident radiation also generates radiation pressure on the cavity wall. The cumulative effects of all pressure forces generate the fluid motion in the trailing edge of the keyhole.)

8.4 EQUATIONS GOVERNING FLUID DYNAMICS

8.4.1 Basic Assumptions

In a fluid, we are concerned with a continuum. That means Eulerian description is more appropriate as opposed to the Lagrangian formulation which is applicable to an
individual particle as in rigid body dynamics. As we are working in Eulerian coordinates, the use of substantial derivative is more appropriate. Therefore, the substantial derivative can be written as

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + (v \cdot \nabla)
\]

The operator D/Dt can operate on velocity v, and be expressed as

\[
\frac{Dv}{Dt} = \frac{\partial v}{\partial t} + (v \cdot \nabla) v = \frac{\partial v}{\partial t} + \nabla(v^2) - v \cdot (\nabla v) \tag{8.8}
\]

The basic assumptions of this mathematical model of fluid motion in the trailing edge of molten pool are as follows:

1. All forces contribute to the fluid motion, these forces are body force and surface forces.
2. The energy absorbed from the laser beam induces all the forces.
3. The material properties of solid and liquid phases are constant.
4. The liquid in the molten pool does not have any surface perturbation.
5. The plasma density in the keyhole is uniform. The electron density does not vary with the depth of the keyhole.
6. The fluctuations due to plasma and/or vapor are neglected, and no other transient effects are considered.
7. The Newtonian relationship is valid for the liquid in the molten pool.
8. The Navier-Stokes equations of motion is applicable. The Navier-Stokes
Equations are given as follows. (8.9)

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + B_i + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_i} \left( \zeta \frac{\partial u_k}{\partial x_k} \right)
\]

(8.9)

Where \( \rho \), density of fluid

\( u_i \), represent velocity components

\[
\frac{\partial u_i}{\partial t}
\]

indicates velocity change with time at a fixed point in space, and

\[
\frac{\partial u_i}{\partial x_j}
\]

velocity gradient

\( P \), pressure

\( \mu \), dynamic viscosity

\( \delta_{ij} \), Kronecker Delta

\( \zeta = \lambda + \frac{2}{3} \mu \), where \( \lambda \) is the second coefficient of viscosity

The equation (8.9) can also be expressed as:

\[
\rho \frac{Dv}{Dt} = -\nabla P + B + \mu \nabla^2 v
\]

(8.10)

The body force \( B \), will be replaced by external fields.
8.4.2 KEYHOLE AND ITS ENVIRONMENTS

The keyhole and its environments is shown in Figure 91. The coordinate \( x \) is in the direction of pool or weld width, \( y \) is the direction of keyhole advancement while \( z \) is in the direction of penetration or melt depth. The cross-section of the keyhole and different regions of phases are shown in Figure 92. All the forces on a three dimensional fluid element are shown in Figure 93.

8.5 STEADY-STATE IN LASER WELDING

In the steady state, the keyhole is not collapsible and sustains the melt pool. The steady-state stability criteria of the keyhole depends on the balance of the forces that tend to keep the keyhole open and sustain the melt opposing the forces that act to obliterate the keyhole.

8.6 FORCES TO SUSTAIN KEYHOLE AND MELT

8.6.1 Laser Beam Pressure

The pressure due to the momentum transfer of photons to the material would aid to form and sustain the keyhole. In our investigation, we define this pressure as radiation pressure, i.e., \( P_{\text{rad}} \). The radiation pressure would depend on the power density on the workpiece.

8.6.2 Vapor Pressure

The vapor pressure in the keyhole would put pressure on the wall of the keyhole. This outward pressure would result in pushing the melt and keep the keyhole open, in the keyhole a pressure gradient exists. The pressure would be increasing with increasing z-
direction. That is, a higher pressure at the bottom of the keyhole and approaching negligible at the surface of the melt.

8.6.3 Recoil Pressure

The escaping metal vapor particles have finite velocities as they leave the surface of beam interaction. Therefore, it is most likely that both the recoil or evaporation pressure would act in the same direction. This pressure will also provide melt depression and the melt will be pushed away and the keyhole would be advanced in the penetration direction.

8.6.4 Plasma Pressure

The plasma in the keyhole\textsuperscript{46} will exert pressure on the keyhole wall. If the plasma density or quasineutral particle is \( n \), then the Lorentz force\textsuperscript{47}, \( \mathbf{F}_L \) is given by

\[
\mathbf{F}_L = q n \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \quad (8.11)
\]

where \( q \) is the charge of the particles, \( \mathbf{E} \) and \( \mathbf{B} \) are electric and magnetic field vectors respectively at a given state of plasma, and \( \mathbf{v} \) is the average velocity of the charged particles. The pressure tends to push back the melt and thus widen the keyhole.

8.6.5 Secondary Radiation Pressure

The secondary radiation is generated in welding due to relaxation processes which are transition from higher excited energy states to lower energy states and the spectral range is in the "blue" region\textsuperscript{46}.
8.6.6 Shield Gas Pressure

In welding plasma suppression techniques are used to disperse the plasma. An inert gas is blown across the plasma from the beam path which enables the laser beam to be focussed unattenuated into the cavity. The plasma suppression technique would put pressure on the vapor and plasma in the keyhole. This would allow plasma to remain in the keyhole. This additional pressure would allow the keyhole to be open and the hole would be broader.

8.7 FORCES ACTING TO COLLAPSE THE KEYHOLE

The forces that tend to close the keyhole and allow the melt to flow back in the cavity are described in this section. The result of the melt flow back in the cavity is the autogenous weld zone after the keyhole has advanced.

8.7.1 Gravitational Force

The gravitational force on the fluid element tends to close the cavity. The gravitational force is proportional to the density of the melt. The pressure is proportional to both the density and height, thus gravitational pressure increases as the penetration increases.

8.7.2 Viscous Force Due to Stress

When a fluid is sheared due to stress, it moves at a strain rate. We define viscous force as a divergence of the viscous-stress tensor. In case of the Newtonian flow, the viscous stress is proportional to the strain rate and the co-efficient of viscosity, thus the viscous force on the fluid element (8.12)
\[ F_\mu = \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \]  \hspace{1cm} (8.12)

The equation (8.12) is valid for incompressible fluid with constant viscosity.

### 8.7.3 Surface Tension

The surface tension force acts against the vapor pressure and other forces described in Sections 8.5.1 for laser welding, where the width of the weld is less than the penetration depth. Therefore in the keyhole mode of laser welding surface tension forces will try to close the keyhole.

### 8.8 FLUID ELEMENT AND EQUATION OF FLUID MOTION

A pressure gradient must exist if there is a net force on the fluid. The resultant of all forces would either keep the element in equilibrium or cause it to move with acceleration. Now, the equation of motion for the fluid element in the molten pool can be constructed taking into account all of the force, namely:

- Laser beam pressure force, \( \nabla P_{\text{ld}} \)
- Pressure force due to vapor, \( \nabla P_v \)
- Recoil pressure force, \( \nabla P_R \)
- Lorentz force, \( qn (E + v \times B) \)
- Secondary radiation pressure, \( \nabla P_B \)
- Shield gas pressure, \( \nabla P_{\text{s}} \)
- Gravitational force, \( \rho g \)
- Viscous force, \( \mu \nabla^2 v \)
- Surface tension, \( \gamma \)
Therefore the equation of fluid in motion can be written as (8.13):

\[ \rho \frac{DV}{Dt} = -\nabla P_{rad} - \nabla P_v + \rho g - \nabla P_v - \nabla P_R + \mu \nabla^2 v + \gamma - \nabla P_g - qn (E + v \times B) \]  

(8.13)

The pressure gradient can be summarized as:

\[ -\nabla P = -\nabla P_{rad} - \nabla P_v - \nabla P_R - \nabla P_B - \nabla P_g \]  

(8.14)

and all the body force can be regrouped into:

\[ F_L = -qn(E + v \times B) + \rho g \]  

(8.15)

then equation (8.13) can be simplified as (8.16):

\[ \rho \frac{DV}{Dt} = -\nabla P + B + \mu \nabla^2 v + \gamma \]  

(8.16)

Equation (8.16) is second order non-linear partial differential equation and quite formidable, but in the next chapter it will be shown that a simplified perturbation model can be used to explain the laser weld instability and a theoretical limit of the speed of laser welds.
CHAPTER 9
LASER WELD INSTABILITY

9.1 INTRODUCTION

In the previous chapter we developed a steady state equation without any surface perturbation. In this chapter, we will introduce surface perturbation as the wave propagating in the fluid, which, in our case, is the weld molten pool. An experimental investigation was made of the dynamics of the melt as a result of interaction with CW CO₂ laser at high speed welding. The hydrodynamic instability of the melt surface was observed as the quasi-periodic structures after solidification. A hydrodynamic correlation of the physical phenomena responsible for the occurrence of this instability was developed and analyzed.

These instabilities (humping) described as the irregular bead, was observed in high speed electron beam welding.¹⁸ In particular, when a single electron beam was used. When the specially designed tandem electron beams were used, the instabilities were eliminated. Arata¹⁸ has not given any satisfactory physical explanation for the occurrence of the instability. Similar humping phenomena was observed by Bradstreet³¹ at high speed arc welding. The experimental investigation of Bradstreet³¹ showed that the humping occurred only in the presence of oxygen, either supplied by shield gas or the presence of oxide in the plate. He claimed that the defect was eliminated with increasing deoxidation. Again, no physical explanation was given for the humping phenomena.
Albright and Chaing\textsuperscript{5} pointed out that jet instability theory can explain the onset of hole formation in the penetration of mode high speed welding but it is inadequate for predicting the onset of undercut and humping. The jet instability theory has been reviewed in the next section. The physical phenomena correlated by Albright and Chaing showed the inconsistency in explaining the transition from stability to instability.

### 9.2 HIGH SPEED WELDING - JET INSTABILITY MODEL

Albright and Chiang\textsuperscript{5} have modeled high speed welding defects through jet instability theory\textsuperscript{48}. The jet instability theory suggests that a jet of liquid will break into drops to minimize surface tension. An expression is developed for a critical break-up length, a distance the liquid jet would travel before turning to individual drops. This expression is

\[ Z_c = 12 \frac{U_z}{\gamma \rho a^3} \]  

where

- \( Z_c \) = critical break-up length of liquid jet
- \( U_z \) = flow velocity of liquid which is taken as welding traverse speed.
- \( \gamma \) = surface tension of the liquid
- \( \rho \) = density
- \( a \) = initial jet radius which is equivalent to the radius of a circle equal in area of the cross-sectional area of the weld.

This model, as Albright and Chiang claimed, has been useful in predicting cutting and hole formation behavior. In the cases of so-called hole formation, the break-up length was less than or equal to pool length. While in the case of smooth welds, the break-up length is longer than the pool length. These two kinds of pool length behavior
establish the instability and stability criteria of weld pools. This surface-tension-based model, though useful in predicting the onset of hole formation, has less reliability for predicting humping and material pile-up next to the hole. Therefore, this jet instability model is clearly inappropriate to explain under-cut or depression in the weld bead.

9.3 FLUID DYNAMIC CORRELATIONS

One of the governing equations of fluid motion is the continuity equation. The integral form of the continuity equation is given by

$$\int_{cs} \rho \mathbf{v} \cdot dA = -\frac{\partial}{\partial t} \int_{cv} \rho \mathbf{v} \cdot dV$$  \hspace{1cm} (9.2)

where $\rho$ is the density of the fluid, $\mathbf{v}$ is the velocity of the fluid motion, $dA$ and $dV$ are the elemental area and volume, respectively, and $cv$ designates the control volume fixed in space and bounded by control surface (cs). A control volume is a finite volume with open boundaries which allows crossing of mass, momentum and energy.

The equation (9.2) physically describes that net rate of mass flow out of the control surface is equal to the time rate of decrease of mass inside the control volume. Applying Gauss' theorem in equation (9.2), we find (9.3):

or,

$$\int_{cv} \nabla \cdot (\rho \mathbf{v}) \cdot dV - \frac{\partial}{\partial t} \int_{cv} \rho \mathbf{v} \cdot dV = 0$$
or,

\[
\int_{\Omega} \left[ \nabla \cdot (\rho v) + \frac{\partial \rho}{\partial t} \right] \, dV = 0 \tag{9.3}
\]

If we take an arbitrary volume, the integrand is zero, then we have the differential form of the continuity equation, therefore, (9.4)

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{9.4}
\]

\[
\frac{\partial \rho}{\partial t} = 0 \quad \text{for the steady state}
\]

and we have,

\[
\nabla \cdot (\rho v) = 0 \tag{9.5}
\]

and for incompressible flow,

\[
\nabla \cdot \mathbf{v} = 0 \tag{9.6}
\]

Equation (9.4) also can be expressed using tensor notation, (9.7)

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho v_i) = 0 \tag{9.7}
\]

The second governing equation in fluid motion is the momentum equation. We can derive the momentum equation by applying the integral form to an elemental volume, as shown in Figure 94. If we consider the shear stresses and normal stresses in the momentum balance and relate the stresses to the velocity components to obtain the momentum equation, we can now apply the integral momentum equation, i.e., (9.8)
\[ F^+ = \frac{\partial}{\partial t} \int_{cv} \nu p dV^+ + \int_{cs} \nu p V^+ dA \quad (9.8) \]

to a fluid element as shown in Figure 94. Before we do that, the total force is decomposed into a surface force \( F \) and a body force \( B \). The surface force accounts for pressure and shear. The body force, described in the previous chapter, could be gravitational force, and is force per unit volume. The momentum equation for a control volume then results in

\[ F^+ \int_{cv} BdV = \frac{\partial}{\partial t} \int_{cv} \nu p dV^+ + \int_{cs} \nu p V^+ dA \quad (9.9) \]

Now from Figure 94, we can write the momentum balance for the x-direction as (9.10)

\[ (\sigma_{11}|_{x,\Delta x} - \sigma_{11}|_{x}) \Delta y \Delta z + (\sigma_{22}|_{y,\Delta y} - \sigma_{22}|_{y}) \Delta x \Delta z + (\sigma_{33}|_{z,\Delta z} - \delta_{33}|_{z}) \Delta x \Delta y + B_x \Delta x \Delta y \]

\[ - \frac{\partial}{\partial t} (\rho u^2)|_{x,\Delta x} - (\rho u^2)|_{x} + \Delta x \Delta z \]

\[ (\rho u v_{y,\Delta y} - \rho v u_{y}) + \Delta x \Delta y (\rho w u_{z,\Delta z} - \rho w u_{z}) \quad (9.10) \]

dividing equation (9.10) throughout and taking the limit as \( \Delta x, \Delta y, \Delta z \to 0 \) and combining with the continuity equation, we get (9.11)

\[ \rho \frac{Du}{Dt} = \rho \left( \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \right) \]
\[-\frac{\partial \sigma_{11}}{\partial x} + \frac{\partial \sigma_{12}}{\partial y} + \frac{\partial \sigma_{13}}{\partial z} + B_x \]  

(9.11)

The y and z directional components can be obtained in a similar way, and they are as follows (9.12):

\[\rho \frac{Dv}{Dt} = \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right)\]

\[-\frac{\partial \sigma_{21}}{\partial x} + \frac{\partial \sigma_{22}}{\partial y} + \frac{\partial \sigma_{23}}{\partial z} + B_y \]  

(9.12)

\[\rho \frac{Dw}{Dt} = \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right)\]

\[-\frac{\partial \sigma_{31}}{\partial x} + \frac{\partial \sigma_{32}}{\partial y} + \frac{\partial \sigma_{33}}{\partial z} + B_z \]  

(9.13)

All the momentum equations (9.11) through (9.13) can be expressed in Cartesian tensor notation: (9.14)

\[\rho \frac{Du_i}{Dt} = \rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial \sigma_{ij}}{\partial x_j} + B_i \]  

(9.14)

The left hand side(LHS) represents the acceleration terms. The \(\partial/\partial t\) term is an unsteady term and signifies a change in time at fixed point. Additional terms in the LHS can be described as convective acceleration, because of choice of Eulerian coordinations system.

For frictionless flow, the shear stresses \(\sigma_{ij} = 0\) i,j \(= 1,2,3\) and \(i \neq j\) and the normal stresses are the pressure. The pressure is assumed to be isotropic. We have
normal stresses \( \sigma_{11}, \sigma_{22}, \sigma_{33} \) as positive in tensions, then \( \sigma_{11} = \sigma_{22} = \sigma_{33} = -P \).

Hence the momentum equation in tensor form are (9.15)

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} \right) = -\frac{\partial p}{\partial x_i} + B_i
\]  

(9.15)

or in component form

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial x} + B_x
\]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = -\frac{\partial p}{\partial y} + B_y
\]

\[
\rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + B_z
\]  

(9.16)

The equations (9.16) are described as the Euler equations. If the flow is incompressible and we assume density to be constant, then Euler equations and the continuity equation constitute four equations with four unknowns. The solution is still very difficult, due to non-linear convective acceleration terms.

9.4 FLUID FLOW EQUATIONS IN THE WELD MOLTEN POOL

The equations of continuity and momentum are expressed for molten pool that associates a surface wave or perturbation. Figure 95 shows the cross-sectional view of molten pool in relation to the solid and keyhole interface. The weld penetration depth is designated as \( z \), which is also described as molten depth.

In Figure 95, we also designate \( \Delta z \) as a wave height, \( v \), the wave or perturbation
propagation velocity, which is related to the welding speed.

Figure 96 shows a wave moving, in a non-inertial frame and Figure 97 shows inertial frame of reference, as would be experienced by an observer travelling with the wave. If the surface wave is due to the combination of vapor pressure, recoil pressure, radiation pressure and plasma pressure exceeding the surface tension and gravitational force, then the perturbation in the form of wave with amplitude Δz will be created and travel as shown in Figures 95 through 97.

The sectional view of melt pool (Figure 96) describes the flow of the wave with an amplitude Δz. The following correlation of fluid motion in weld pool are considered:

- Depth of weld pool (z) is equivalent to the weld penetration.
- Weld width of the pool, W
- Assume negligible shear τ_B = 0 at the bottom of the weld pool.
- The density of molten pool, ρ_m is constant within the region of our interest.
- The flow is irrotational and incompressible now introducing the so-called fluid dynamic concept of control volume as in Figure 97, (we find the potential at z and z+Δz, which are ρ_m gz and ρ_m g(z+Δz) respectively).

The integral form of continuity equation becomes,

\[ ρ_m vzw = ρ_m (v-δv) (z+Δz)w \tag{9.17} \]

or, \( zv = (v - δv) (z+Δz) \)

\[ v-δv = \frac{zv}{(z+Δz)} \]
\[ \delta v = v - \frac{\Delta z}{z + \Delta z} \]

\[ \delta v = v - \frac{zv}{z + \Delta z} + \frac{zv + v\Delta z - zv}{z + \Delta z} \]

Therefore

\[ \delta v = v \frac{\Delta z}{z + \Delta z} \quad (9.18) \]

From the equation (9.18), it is imperative that the perturbation induced velocity, \( \delta v \) would be negligible if the melt depth is significantly higher. Therefore, the instability would occur as \( \Delta z \rightarrow z \). Again, \( z \) is the penetration of weld.

Prior to examining the velocity of processing that would create this hydrodynamic instability, we would review the conservation of momentum. The rate of change of the momentum of the fluid element can be described as the sum of net rate of outflow momentum across the control surfaces and rate of accumulation of the momentum within the control volume. In the case of a steady state, the rate of accumulation of momentum within the control volume is equal to zero. Thus, for steady state, the force on the fluid element is equal to the net rate of outflow of momentum across the control surface. This can be formulated mathematically as follows

\[ \sum F_i = -\frac{d(mv)_{out}}{dt} - \frac{d(mv)_{in}}{dt} \quad (9.19) \]
For the steady flow, equation (9.19) can be expressed as the scalar equations in terms of forces and velocities in the x, y, and z directions. Again considering the control volume of Figure 97, and such that the control surface is normal to the velocity where it intersects the flow, we showed the situation in Figure 97 by arrows, and we are dealing with the molten metal contained within Sections 1 and 2 at a time t. The molten metal moves to a new position during the time interval dt. During this short interval, we will assume that the molten metal moves an infinitesimal distance ds₁ and ds₂ at sections 1 and 2 respectively.

The flow is also restricted to steady flow, so equation (9.19) could be applied. The momentum crossing the control surface of section 1 during the interval dt is

$$(\rho_m wz ds_1) \nu$$

and at section 2, the momentum crossing is

$$\rho_m w (z+\Delta z) ds_2 (\nu - \delta \nu)$$

Since the control volume intercepts the velocity at right angles,

$$\nu = \frac{ds}{dt},$$

therefore the above two momentum expressions become

$$(\rho_m wz \nu) \nu$$

and

$$\rho_m w (z+\Delta z) \nu (\nu - \delta \nu)$$
from the equation of continuity,

\[ \rho_m w z v = \rho_m w (z + \Delta z) v_z \]

Therefore equation (9.19) becomes

\[ \sum_i F_i - \rho_m w z v (v - \delta v - v) \quad (9.20) \]

The forces acting on the control volume shown in Figure 97 are hydrostatic pressure force and friction; we have assumed friction to be negligible. The gravitational potentials at sections 1 and 2 are \( \rho_m g z \) and \( \rho_m g (z + \Delta z) \) respectively.

The pressure force on any vertical section of width \( w \) is given by (9.20)

\[ F_N = \int_0^z \rho_m g w z d z - \frac{1}{2} \rho_m g w z^2 \quad (9.21) \]

Similarly

\[ F_{N z + \Delta z} = \int_0^{z + \Delta z} \rho_m g w (z + \Delta z) d (z + \Delta z) - \frac{1}{2} \rho_m g w (z + \Delta z)^2 \quad (9.22) \]

The momentum relation is a balance between net hydrostatic pressure force and momentum, and so equation (9.20) can be rewritten as

\[ \frac{1}{2} \rho_m g w z^2 - \frac{1}{2} \rho_m g w (z + \Delta z)^2 - \rho_m v w z (v - \delta v - v) \]
or,

\[-v\delta \nu \rho_{\infty} w z = \frac{1}{2} \rho_{\infty} g w (z^2 - (z + \Delta z)^2) - v\delta \nu z = \frac{1}{2} g (z^2 - z^2 - 2z\Delta z - \Delta z^2)\]

\[-v\delta \nu = g (-\Delta z - \frac{\Delta z}{2z})\]

Therefore,

\[v\delta \nu = g \Delta z \left(1 + \frac{\Delta z/2}{z}\right)\] (9.23)

recall the relation for \(\delta \nu\) derived from the continuity equation, and eliminating \(\delta \nu\) from equation (9.23),

\[v \left(\frac{\Delta z}{z + \Delta z}\right) = g \Delta z \left(1 + \frac{\Delta z/2}{z}\right)\]

or

\[\frac{v^2}{(z + \Delta z)} = g \left(1 + \frac{\Delta z/2}{z}\right)\]

or

\[v^2 = g \Delta z (1 + \frac{\Delta z/2}{z})\]

Hence the velocity at which the perturbation travels is

\[v = g \Delta z \left(1 + \frac{\Delta z}{z}\right) \left(1 + \frac{\Delta z/2}{z}\right)^{1/2}\] (9.24)
v is related to the welding speed at which the wave of amplitude $\Delta z$ travels opposite to the direction of welding.

9.5 DYNAMIC SIMILITUDE

In hydrodynamics, some of the very important results may be obtained from dimensional arguments. The relevant physical parameters may be combined into dimensionless quantities that characterize the flow in fluid dynamics. In incompressible flow, the equations of continuity and motion are required to describe the flow as we have explained in the previous sections. In our case (that is), melt flow in the trailing edge of keyhole can be described as "incompressible flow with a free surface." We have considered in the previous sections that the governing forces in the melt pool are inertia and gravity only. If any two such systems (i.e., two different melt pools) are dynamically similar, then the corresponding forces must be in the same ratio of two.

For a system that involves gravity and inertia, a ratio can be obtained called "Froude number", or $F_r$, to classify the flow. The Froude number $F_r$ can be formulated as

$$F_r = \frac{v}{(gz)^{1/2}} \tag{9.25}$$

where $v$, the velocity of flow,

g, acceleration due to gravity.

$z$, depth of the molten pool.

In the next section, we will experimentally correlate $F_r$ (Froude number) to stability and instability of laser welds.
9.6 EXPERIMENTAL CORRELATION

The sound laser weld bead was defined previously as the bead without any instability. Instabilities in turns are designated as humping or perturbation. The perturbation is also associated with undercut and through-thickness porosity. Through-thickness porosity is also described as "holes." Before we pursue experimental correlation of instability, we also should define stability conditions. The stability condition of the weld bead physically characterizes weld surface without any surface defects. These surface defects are described as humping, etc., in case of instability. The molten pool depth has been given in equation (9.24),

\[ v^2 = g z (1 + \frac{\Delta z}{z})(1 + \frac{1/2}{z}) \]  \hspace{1cm} (9.24)

In equation (9.24), the greater the perturbation \( \Delta z \), the faster the wave speed \( v \).

In the limit of an infinitesimal perturbation \( \Delta z \to 0 \), the velocity becomes

\[ v_0^2 = g z \]

or

\[ v_0 = (g z)^{1/2} \]  \hspace{1cm} (9.26)

Therefore, the stability condition can be defined as an infinitesimal perturbation which is (9.27)

\[ \Delta z = 0 \]  \hspace{1cm} (9.27)
Now the Froude number for stability condition is given by \( F_r \),

\[
F_r = \frac{v_o}{(gz)^{1/2}} = 1 \quad (9.28)
\]

The theoretical value of the weld speed for stability condition for the sheet steel of thickness 0.8 mm is 11.92 m/min. The experimental value of the weld speed we have obtained in our investigations is 11.0 m/min. At this experimental value of the weld speed, no surface perturbation is observed.

The instability condition is defined by \( F_r \geq 1.0 \) (9.28). The theoretical value of welding speed where we should see the instability is greater than 11.92. We have encountered instability at welding speed greater than 13.0 m/min. up to 20 m/min.

The further experimental correlation was made by measuring the perturbation height of the high speed bead-on-plate welds. The welding speed was calculated using perturbation relations (Equation 9.24) which are developed for free surface molten pool in this research. The perturbation heights were measured after solidification. The measured perturbation heights and calculated speeds are shown in Table 15. The calculated speeds varied from 15.72 m/min. to 21.32 m/min. due to corresponding variation of the measured perturbation heights. The significance of these results is discussed in Chapter 10.
CHAPTER 10
DATA ANALYSIS AND DISCUSSION

10.1 INTRODUCTION

In this chapter, an analysis and interpretation of the Taguchi results will be given. The analysis is based on the review of "Taguchi Experiments - Laser Welding Optimization" of Chapter 4. In addition to data analysis, the characterization of one series of welds in the Taguchi matrix will be revisited. The characterization is made here to support the results from optical microscopy in Chapter 7 and to aid the discussion of physical mechanisms of laser welds.

In the general discussion, prominence will be given to Taguchi results applied to butt weld optimization, and the instability threshold for high speed laser welds. We will also compare the instability result of prior researchers based on instability relations which we proposed. We will highlight our discussion on physical performance of the welds and related test results.

10.2 HIGH-SPEED BEAD-ON-PLATE LASER WELDING

Prior to butt weld optimization and Taguchi experiments, high speed bead-on-plate welding was completed. In this phase, process parameters were chosen as those that appeared to make the best weld. These process parameters formed the base parameter settings for the butt welding optimization. The high speed bead-on-plate welding was conducted as experiments 1 through 17 of Table 9. The visual examination showed humping (instability) associated with undercut for experiments 1 and 2. In these two
experiments, the laser beam focal position was placed on the top of the surface, which is the 0 defocus position or the reference position. At the position of focus, the energy density of laser beam is the highest due to the smallest focus diameter of beam. The spot sizes of the focused beam for both the x- and y- direction are shown in Fig. 48.

The high power density associated with the smallest focal spot size creates a narrow molten pool. The laser beam diagnostic system (Laserscope UFF100) is unable to determine the isometric projection of the intensity distribution at the focus position. Due to this limitation, no beam pattern at the focal position is observed which can also contribute to the humping or instability. An insight into this instability problem can be afforded through examination of the keyhole mode of laser welding.

In the keyhole mode of high energy density welding (such as laser and electron beam), the beam creates a through-the-thickness vapor and plasma cavity which traverses along the weld seam (as the beam or work-piece is translated). The melting occurs immediately ahead of the keyhole, and liquid metal flows around it. As the welding speed increases, the width of the molten pool in the front edge of the cavity decreases. Because of the decreasing molten pool width, the molten metal is forced to move at higher speed between the narrow region of vapor and solid interfaces. The fluid (molten metal) motion will develop a surface wave (which we described as an instability or perturbation) behind the laser beam. This fluid motion simulates the associated surface wave analogous to a high speed ship travelling through water. The development of a surface wave is observed at a welding speed of 15 m/min. with the focus position at the surface. In Experiments 1 and 2, the small spot diameter and high speed contributed to
the instability. The small spot diameter restricts the circumferential flow around the keyhole, and also creates narrow elongated channels with a higher surface perturbation in the trailing edge of the keyhole. In Experiment 3, the beam was defocussed to +3 mm; i.e., 3 mm into the work-piece. The beam spot diameter was larger than the previous "0" position, being more elongated in both the x- and y- directions. These values of focussed beam diameters are shown in Fig. 48. Though the focussed intensity distribution was not measured due to the limitations of the device (Laserscope), a measurement was taken at the defocus position of +8 mm. The isometric projection of the intensity distribution and the beam contour (Fig. 40) show a relatively non-uniform intensity distribution. The wider bead and non-uniform distribution resulted in visually better welds than those produced in Experiments 1 and 2. In Experiment 4, the defocus was changed to -3 mm. The intensity distribution and the beam contours are shown (for -8 mm) in Figure 39. Because of lack of symmetry of intensity distributions at +3 mm and -3 mm defocus positions, the Experiment 4 resulted in an irregular bead, because the intensity threshold is still very high due to small spot size. The defocus position changed to +2.75 mm, gives an intensity threshold which is comparatively lower than the previous case (Experiment 5) and focussed beam spot size is larger. At this threshold spot diameter no surface perturbation was observed.

Experiments 7 through 17 were conducted to optimize the process parameters such as shield gas flow rate, nozzle diameter, speed, and penetration of the weld. Experiment 17 used the following process parameters: power 9 kW, shield gas He with nozzle diameter of 3.3 mm, flow rate 20 l/min, defocus position +3.5 mm, and speed 16 m/min.
These process parameters produced welds with full penetration and a chevron-pattern top bead. The process parameters of Experiment 17 are used as the initial parameter setting for laser butt welding optimization.

10.3 BUTT WELDING PROCESS OPTIMIZATION

The butt welds were conducted in Experiments 18 through 50 to set up design parameters for the Taguchi orthogonal array. The process parameters are shown in Table 10 of Chapter 7. The butt welds were optimized at various speeds (16.02 m/min. to 9 m/min.) with a shield gas of helium or argon with different flow rates. The focus position was also varied. The depth of focus for butt welding optimization was limited within a range 0.5 mm. The small depth of focus was obtained due to the shorter focal length of the focusing optics and the smaller beam size (Fig.39). The shield gas type, whether helium or argon, had an insignificant effect at high speed welding, though the ionization potential of helium is higher than argon.

10.3.1 Erichsen Cup Test - Butt Welded Specimen

The Erichsen cup test was conducted on butt welded samples of Experiments 24, 27, 30, 31, 32 and 33. The purpose of selecting this particular series was that they were welded at various speeds and at different defocus positions. The process parameters used for Experiments 24 through 33 are shown in Table 10. The Erichsen cup tests of 24-series showed lowest deformation values and weld failure occurred in the longitudinal direction of the seam. The weld micrograph revealed lack of full penetration and severe undercut at the top bead. The lack of penetration and undercut is due to the high welding speed. The deformation of the welds of Experiments 31 and 32 were also low due to
severe undercutting of the top bead of welds. Series 27, 30, and 33 had deformation values comparable to base materials. Series 27 and 30 were welded at same focal position but at speeds of 12 and 13.02 m/min. respectively. Series 33 was welded at a defocus position of +3.5 mm at a velocity of 13.02 m/min. Series 33 samples showed failure in the weld transverse to the weld seam, which is the typical failure usually observed in the Erichsen test cup. Though the ductility behavior of the laser welded sheet steels are comparable, yet there is as much as 6% reduction in ductility which occurred in some cases. This loss of ductility is due to the increased hardness of the weld seam.

10.4 TAGUCHI DESIGN OF EXPERIMENTS - LASER BUTT WELDING OPTIMIZATION

All data and results of laser welded (Taguchi experiments) specimens are summarized in Table 12 of Chapter 7. The data and responses (tensile strengths) are analyzed based on the discussion of Chapter 4. The analyses of data and responses of Taguchi samples are shown in the Analysis of Variance (ANOVA) Table (Table 16). The qualitative affirmation of the significant contribution of each process variable is described in the last column, designated as $\rho$, percent of contribution. The process variable significance is based on its contribution to the production of quality welds. Quality welds are described as the welds that have the tensile strength of the base materials. Furthermore, failure should occur in the base materials and not at the weld. In our investigation, the significant process parameters are speed, material and shield gas flow rate. The percent contribution of each of the process parameters are 39.95% for speed, 8.91% gas flow rate, 15.35% of nozzle diameter and finally, 18.15% depends on
material choice. The Taguchi analysis showed an experimental error of 16.69%. Due to this error, the only significant parameters in our experiment are speed and material. The laser power has the lowest significance in our experiments. The significance of focus position is also very low due to the very small discrete change in the levels allowed. The insignificance of laser power is quite obvious, because Taguchi experiments 5 through 8 use laser power substantially lower than 9.0 kW to achieve welding speed 7 m/min. to 11 m/min. The highest welding speed was 13.0 m/min. at power 9.0 kW.

The definition of the columns that represent degrees of freedom, sum of squares, variance ratio and pure sum of squares have been discussed in Chapter 4. The industrial engineers might find the data in those columns valuable. Because process optimization should focus only on robust processes, we have limited our discussion to the percent contribution of each process variable.

The average response for each of the process and material parameters was calculated and plotted to quantify their relative impact. Figure 98 shows the plot of average responses for factors A to G. From the plot of average response, the optimal levels are selected for each of the controllable parameters. The optimal levels, in our case, would provide the highest tensile strength. The analysis of Taguchi results showed that the process variables: A1: Power - 9 kW, B2: Focus position - +3.5 mm, C1: Traverse speed - 13 m/min., D2: Gas flow rate - 20 l/min., E1: Nozzle diameter - 3.3 mm, and G1: Material - IF 18 provided the highest tensile strength.

If the material combination is unavoidable, which is usually the case for the tailored blank welding, we need to analyze our data considering different material
combinations. The material combination we used in our experiment is IF 18 and ST 14. These are interstitial free steel and cold rolled mild steel. We also like to consider the contribution of various process parameters from the ANOVA Table (Table 16). From this, we can infer that laser power contributes the least. Therefore, in our next analyses we have considered power A2 and material G2. The new analyses are shown in Table 17. It is evident from Table 17 that the tensile strengths are comparable to those of the base materials for both cases (power: A2 and material: G2). This implies that Taguchi methods applied to laser butt weld optimization could a provide robust process.

10.5 ANALYSIS AND DISCUSSION OF WELDS THAT PROVIDED POOR PHYSICAL PERFORMANCE

In support of the initial results reported in Chapter 7, where we have optically characterized the welds, for bead profile, penetration, surface topography and so on, a further analysis of poor welds is given in this section. The welds that have both low tensile strength and fatigue life are classified as poor welds. This classification is also valid for welds that lack full penetration and have a wider heat affected zone, higher porosity, and so on. The welds of Experiment 5 in the Taguchi orthogonal array fit all these criteria. In this section, we have characterized those welds through micro-sectioning, and recreated them in three-dimensions. This recreation of the welds provides further insights in the effects of the process parameters used.

10.5.1 Visual and Optical Characterization - Taguchi

Samples of Experiment No. 5

The results of visual and optical characterization are given in Chapter 7. The
optical examination showed lack of penetration and crack line in the bottom; the top and bottom sides of the weld had a wider heat affected zone. The wider heat affected zone implied that more laser energy had been transferred laterally in the sheets than along the weld seam. This can create separation of the sheets at the seam. The wider HAZ also can be a combined result of improper shield gas application and a much slower speed. In our experimental case, the shield gas flow rate was in lower level (that is, 15 l/min.) and the weld speed only 7 m/min. It is very likely that improper plasma suppression and slower welding speed resulted in a wider heat affected zone.

10.5.2 3-D Reconstruction of Taguchi Sample of Experiment 5

To diagnose the lack of full penetration and intermittent bottom surface disruption, the laser welds were micro-sectioned and polished. The longitudinal bead profile was rough cut in two halves and each half was polished to reveal microstructures and weld cross-sections. The cross-sections were taken at less than 1 mm interval. The cross-sections revealed information such as penetration depth, weld area, heat affected zone, top and bottom transverse profile. The transverse profiles also showed undercut and the dimension of the crack line. Some examples of cross-sections of the weld are shown in Figures 99 through 102. These optical micrographs are placed under transparent measuring grids to evaluate the dimensions of the weld cross-sections. The transverse and longitudinal dimensions of weld cross-sections and bead profile formed the basis for the 3-dimensional reconstructions of the weld profile. The transverse dimensional informations are plotted as the two-dimensional trace of the entire weld boundary including the crack line. The boundary of the weld cross-sections are shown in Figures
103 through 124. This dimensional information was downloaded to reconstruct 3-D weld profiles. The reconstructed weld profiles are shown in Figures 125 through 127.

The weld of Taguchi sample (Exp. 5) failed in tensile and fatigue tests due to the pre-existing crack in the weld seam. This crack, as we have discussed previously, is due to the improper energy transfer on the weld seam. The low speed and insufficient shield gas flow rate allowed laser energy decoupling onto the work-piece. The decoupling of the laser beam resulted because of sufficient plasma formation above the keyhole or the weld seam. This plasma formation is evident from observed wider top weld bead, which resulted because of intense plasma heating.

The inconsistent weld depths are observed from the weld cross-sections which is produced by plasma fluctuations and instability of beam emission.

10.6 HIGH SPEED WELD INSTABILITY

The analytical expression for the high speed weld instability is given in Chapter 9 where experimental correlations were also made. The experimental weld speed is somewhat lower than the calculated value from the instability relation. The calculated speeds varied from 15.72 m/min. to 21.32 m/min. While the experimental speed is 15.0 m/min., the instability relation developed by the author assume no temperature gradient driven flow in the molten pool. The temperature gradient driven flow may add to the surface perturbation as a secondary process. Due to the enhanced perturbation, the calculated value of weld speed is higher than the experimental values.

The dynamic similitude, taken to be the Froude number, can describe the onset of instability. In the present case, \( F_r > 1 \), will result in instability. The experimental
observation of the author verifies this instability criteria.

The author has also correlated the experimental results of Albright and Chaing, who observed instability in carbon steel (AISI 1015) at welding speed of 10.16 m/min. According to the present author, instability should have occurred at 8.13 m/min. Albright and Chaing did not report any results at weld speed 8.13 m/min.
CHAPTER 11
CONCLUSIONS AND RECOMMENDATIONS

11.1 STATEMENT OF OBJECTIVES

There were five objectives of this research. The first was to review and assess the body-in-white manufacturing processes, material usage and laser welding aspects to produce integrated material sheets. The second objective was to optimize the high speed laser welding process and to suppress the related physical phenomena of instability or surface perturbations. The third objective was to experimentally develop process parameters for welding of body-in-white materials and to characterize the physical behavior of welds. The fourth objective was to develop a physical insight of high speed laser welding process that formulates the basis of the instability. And the final objective was to recommend a quantitative solution to high speed welding and robust process parameters.

The results of each of these research objectives are presented in sections 11.2, 11.3, 11.4 and 11.5 respectively. All of the recommendations are discussed within the context of sheet steel used for body-in-white applications. The recommendations presented are the combinations of several existing practices and ideas along with the findings of this research.

11.2 LASER WELDING AND BODY-IN-WHITE MANUFACTURING PROCESSES

The laser butt welding of automotive sheet steels brings unique benefits in
manufacturing of body-in-white parts. They are as follows:

- Reduction of manufacturing steps due to elimination of dies and assembly operations
- Selective physio-chemical properties in welded blanks
- Variation reduction of parts
- Higher material yield due to less engineered scrap and offal reclamation
- Less stress risers due to elimination of spot welds
- Better corrosion resistance
- Potential weight reduction

Laser welding has been adopted for integrating sheet steels in a few isolated automotive applications. Its use in mass-production is limited due to economic reasons though its benefits are duly recognized by the automotive industry worldwide. The laser butt welding applications demand progressively higher travel speeds to reduce costs.

11.3 SUMMARY OF THE RESULTS FOR THE OPTIMIZATION OF WELDING SPEEDS

The industrial applications of welding processes demand higher speeds for economic reasons. However, the maximum speeds are limited by the defects in the weld bead, which have been observed to occur at a certain threshold value of the keyhole travel speed.

- The threshold speed where the surface instability observed is 13.0 m/min.
- At speeds higher than the threshold values, a quasi-periodic surface perturbation with holes was observed.
- The heights of the surface perturbation are quite uniform.
The surface perturbation and holes were observed at certain beam and process parameters.

The instability is sensitive to the following process parameters:

i) Focal position

ii) Beam profile

iii) Laser power

iv) F # of focusing elements

The instability is less sensitive to:

i) Shield gas type

ii) Plasma suppression

A weld speed of 16 m/min. without any visual defects was achieved at the following process parameters for bead-on-plate welding:

- Beam parameters employed were power 9 kW, non-uniform isometric distribution of beam, focusing optics of focal length 200 mm, and defocus position at +3.5 mm.

- Process parameters employed shield gas type - Helium, nozzle diameter 3.3 mm, standoff 10 mm, angle of projection 45°.

11.3.1 Butt Welding Optimization

Butt welding was optimized with the base parameters developed during bead-on-plate welding. The following conclusions were made from our observations and Erichsen cup test:

- The combination of high speed and higher defocus would result in lack of full penetration.
A higher defocus position must be combined with lower speed.

- A lower speed and lower defocus position would result in full penetration weld.
- At high welding speeds, weld penetration is insensitive to shield gas type.
- The butt welds with full penetration retain their formability behavior with a reduction of ductility of approximately 6%.

**11.3.2 Taguchi Experiments - Laser Butt Welding**

The following conclusions may be drawn from Taguchi experiments of laser welding in the butt joint configurations:

- In laser welding optimization, the significant parameters are speed, material and shield gas flow rate.
- The percent of contribution of each parameter: Power - 0.97%, focus position - insignificant, speed - 39.94%, gas flow rate - 8.91%, nozzle diameter - 15.35%, material - 18.15%.
- Optimized factors from the plots of process average response are: Power - 9 kW, focus position - +3.5 mm, speed - 13 m/min, gas flow rate - 20 l/min, nozzle diameter - 3.5 mm and material - IF 18.
- Different material combinations and power can be used in laser butt welding without much sacrifice of strength.
- The tensile and fatigue performance of Taguchi samples of certain of these experiments is inconsistent due to partial penetration of welds.

**11.4 High Speed Laser Weld Instability**

A hydrodynamic model is developed to correlate the high speed weld instability
and laser melt movement.

- The onset of instability is defined by Froude number, \( F > 1.0 \).
- The experimentally observed instability occurs at a welding speed of 13.0 m/min while the theory predicts a threshold value of 11.92 m/min.
- The calculated speed from the instability relation is lower than the experimental value.
- The instability theory does not consider the temperature gradient driven flow.

### 11.5 RECOMMENDATIONS

The following recommendations are made for high speed laser butt welding of automotive body-in-white sheet steels:

- The transverse alignment of laser beam at the joint is very critical to transfer energy to the material of seam. Therefore, the focussed beam should be placed in such a way that it provides energy at the seam.
- The fitup condition for high speed is more critical than welding at lower speeds.
- Non uniform intensity distribution or higher order beam mode is useful for practical high speed weld applications.
- The high F # optics should be used to obtain a higher depth of focus which will increase process windows and will also compensate for material thickness variations.
- The welding process speed should be as high as possible. That would provide high process efficiency, less heat input and higher productivity.
- At high welding speed, less shield gas may be used.

### 11.6 FUTURE WORK

The following recommendations are made for future work:
- To gain further understanding of the applicability of the Froude number limitation proposed in this dissertation, laser welding should be conducted at higher speeds (more than 16 m/min) and on sheets of different thicknesses.

- Different F # optics need to be investigated to increase welding speed and develop process boundaries. This may be accomplished by varying the telescope position.

- Taguchi experiments may be conducted to investigate the following:
  
  i) Use of various laser types (i.e., lasers with different emission wave lengths) such as Nd+YAG and CO₂ which corresponds to wave lengths 1.06μm and 10.6μm respectively.

  ii) Different focussing optics that have higher focal lengths should be investigated.

  iii) Different material parameters such as strengths, coatings, varying thickness ratios should be investigated.

  iv) Laser power could be varied.

  v) Different mode structures may be used.

  vi) Interactions between all the factors (beam and process parameters) mentioned above should be considered.

- Different melt pool cross-sections should be investigated to further validate the instability theory and onset of instability. The present theory has no pool width dependence.

- Real time measurements of instability would provide more insights into the high speed laser welding and its limitations.
RIBLIOGRAPHY


11. R. Corrodi, Soudronic AG, Switzerland, Private Communications (1994).


28. J. T. Luxon, GMI Engineering and Management Institute, USA, "Private Communications," (2990).


Table 1. The Conventional Manufacturing Processes And Advantages And Disadvantages For Both Divided And Single Sheet Blanks

<table>
<thead>
<tr>
<th>Compared items</th>
<th>Divided type</th>
<th>One-sheet type</th>
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<td>Schematics</td>
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<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>① Cleanness</td>
<td>bad</td>
<td>good</td>
</tr>
<tr>
<td>② Number of dies</td>
<td>20 dies</td>
<td>4 dies</td>
</tr>
<tr>
<td>③ Accuracy</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>④ Material yield</td>
<td>high (65%)</td>
<td>low (40%)</td>
</tr>
<tr>
<td>⑤ Material flexibility</td>
<td>selectable</td>
<td>fixed</td>
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<tr>
<td>⑥ Weight</td>
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</table>

Integrated side member by laser welded blanks
Table 2. Orthogonal Array $L_8(2^7)$

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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>Results</th>
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Table 3. ANOVA Table

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<th>Mean Squares</th>
<th>Variance Ratio</th>
<th>Pure Sum Of Squares</th>
<th>Percent</th>
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<td>$R$</td>
<td>&quot;V&quot;</td>
<td>Contr $\rho(%)$</td>
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<td>Exp. No.</td>
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<td>Nozzle Diameter</td>
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<td>------------</td>
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### TABLE 5. Parameters & Levels

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<th>Parameters</th>
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<tr>
<td>(A) Laser Power</td>
<td>1. 9 kW</td>
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<td>2. 7.5 kW</td>
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<td>(B) Beam Focus Position</td>
<td>1. 3.25 mm</td>
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<td>2. 3.50 mm</td>
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<td>(C) Weld Speed</td>
<td>1. 13 m/min.</td>
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<td>2. 9 m/min.</td>
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<tr>
<td></td>
<td>3. 7 m/min.</td>
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<tr>
<td></td>
<td>4. 11 m/min.</td>
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<tr>
<td>(D) Gas Flow Rate</td>
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<td>2. 20 l/min.</td>
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<td>(E) Nozzle Diameter</td>
<td>1. 3.3 mm</td>
</tr>
<tr>
<td></td>
<td>2. 5.0 mm</td>
</tr>
<tr>
<td>(F) Dummy</td>
<td></td>
</tr>
<tr>
<td>(G) Y Material</td>
<td>1. IF 18</td>
</tr>
<tr>
<td></td>
<td>2. ST 14</td>
</tr>
</tbody>
</table>
Table 6. DATA SHEET
LASER WELDING OF FATIGUE SAMPLES

EXPERIMENT #

DATE: 

OPERATOR: 

==========================================================================================================

MATERIAL

__________________________________________________________________________

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<thead>
<tr>
<th>X-Side</th>
<th>Y-Side</th>
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<tr>
<td>Bare</td>
<td>Bare</td>
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Thyssen Designation:

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<th>St 14</th>
<th>ZSIE 340</th>
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</thead>
</table>

| IF 18 | St 14 | ZSIE 340 |

Rolling Direction:

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<th>Perpendicular</th>
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| Parallel | Perpendicular |

Chemistry: 

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<td>2.5 mm</td>
</tr>
</tbody>
</table>

<table>
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<th>Thickness</th>
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<tr>
<td>1.25 mm</td>
</tr>
<tr>
<td>2.5 mm</td>
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</table>

==========================================================================================================

WELDING PARAMETERS

Laser Type: 

<table>
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<tr>
<th>R-S 850</th>
</tr>
</thead>
</table>

| R-S 10 kW |

Laser Power at Work-Piece: 

Beam Mode: TEM (Attach Profile)
Table 6. (Cont’d)

**Data Sheet (Page 2)**

<table>
<thead>
<tr>
<th>Beam Focus Position</th>
<th>(W.R.T. Flash Surface)</th>
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</thead>
<tbody>
<tr>
<td>Beam Diameter (mm)</td>
<td></td>
</tr>
<tr>
<td>Focal Length of Mirror (mm)</td>
<td></td>
</tr>
<tr>
<td>Position of Focal Point</td>
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</tr>
<tr>
<td>F #</td>
<td></td>
</tr>
<tr>
<td>Diameter of Focused Spot Size</td>
<td></td>
</tr>
<tr>
<td>Welding Speed</td>
<td></td>
</tr>
<tr>
<td>Gap (mm)</td>
<td>(Attach Vision Data)</td>
</tr>
<tr>
<td>Shield Gas Type</td>
<td>Argon</td>
</tr>
<tr>
<td></td>
<td>Helium</td>
</tr>
<tr>
<td>Flow Rate (CFH - CFM) at T</td>
<td>at N at R</td>
</tr>
<tr>
<td>Flow Rate at N</td>
<td>Flow Rate at R</td>
</tr>
<tr>
<td>Shield Gas Directions (in degrees)</td>
<td>T N R</td>
</tr>
<tr>
<td>Air Cooling at T (Bar)</td>
<td>R (Bar)</td>
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<tr>
<td>Nozzle Stand-off/Positions</td>
<td>(Attach Sketch)</td>
</tr>
<tr>
<td>Nozzle Diameter (mm) T N R</td>
<td></td>
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<tr>
<td>Shield Gas Flow Direction</td>
<td>(W.R.T. Weld Pool)</td>
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Quality Control (Attach Acoustic Scan)
Table 7. Chemistry and Physical Properties of IF 18 Steel

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<th>Type of Deoxidation</th>
<th>Chemical Composition %</th>
<th>Mechanical Properties</th>
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<td>Ti max.</td>
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<td>Special-killed</td>
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</table>
Table 8. Chemistry and Physical Properties of ST 14 Steel

<table>
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<th>Type of Deoxidation</th>
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<th>Mechanical Properties</th>
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<tbody>
<tr>
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<td>C max. N max.</td>
<td>Tensile Strength (MPa)</td>
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<td>0.08 Fixed</td>
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TABLE 9. BEAD-ON-PLATE WELDING

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Power (kW)</th>
<th>Gas</th>
<th>Flow Rate (l/min)</th>
<th>Focus Position (mm)</th>
<th>Weld Speed (mm/s)</th>
<th>Nozzle Diameter (mm)</th>
<th>Angle (°)</th>
<th>Stand off (mm)</th>
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### TABLE 10. BUTT WELDING OPTIMIZATION

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<th>Experiment No.</th>
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### TABLE 10. BUTT WELDING OPTIMIZATION (Cont’d)

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<tr>
<th>Experiment No.</th>
<th>Power (kW)</th>
<th>Gas</th>
<th>Flow Rate (l/min)</th>
<th>Focus Position (mm)</th>
<th>Weld Speed (mm/s)</th>
<th>Nozzle Diameter (mm)</th>
<th>Angle (°)</th>
<th>Stand off (mm)</th>
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Table 11. Erichsen Cup Test Results

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<th>Butt Welding Expt. No.</th>
<th>1st Top (mm)</th>
<th>2nd Top (mm)</th>
<th>3rd Top (mm)</th>
<th>1st Bottom (mm)</th>
<th>2nd Bottom (mm)</th>
<th>3rd Bottom (mm)</th>
<th>Base Material (mm)</th>
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<td>12.6</td>
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### Table 12. Orthogonal Array L₈ - Process Parameters

<table>
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<tr>
<th>Exp. No.</th>
<th>Laser Power (kW)</th>
<th>Beam Focus Position (mm)</th>
<th>Weld Speed (m/min)</th>
<th>Gas Flow Rate (l/min)</th>
<th>X Galv.</th>
<th>Y Galv.</th>
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<tr>
<td>1</td>
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<td>ST 14</td>
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<td>ST 14</td>
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<td>IF 18</td>
<td>ST 14</td>
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### Table 13 - IF 18 BASE MATERIAL/UNWELDED

<table>
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<th>Load (N)</th>
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<th>Remarks</th>
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<td>4,698,410</td>
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<tr>
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<tr>
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<td>5,180,980</td>
<td>R</td>
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<td>1,008,580</td>
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<tr>
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*F=Failure  
*R=Runout
Table 14 - IF 18 MATRIX/WELDED

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<th>F/R*</th>
<th>Remarks</th>
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*F=Failure  
R=Runout
Table 15. High Speed Weld Perturbation and Calculated Weld Speed (Experimental Correlation)

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<th>Perturbation (mm)</th>
<th>Velocity (m/min.)</th>
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<td>1.2192 mm</td>
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<td>0.6604 mm</td>
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<td>0.5588 mm</td>
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<td>1.1811 mm</td>
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Table 16. ANOVA Table - Taguchi Optimization of Laser Welds

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<th>Source</th>
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<th>$V_T$</th>
<th>$V$</th>
<th>$R$</th>
<th>$V^I$</th>
<th>$\rho(%)$</th>
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Table 17. Process Average - Raw Data

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<th>B1</th>
<th>C4</th>
<th>D2</th>
<th>E1</th>
<th>G1</th>
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</thead>
</table>

Equals 978.75000 +/- 98.537000
(from 1077.28700 to 880.21300)
**Table 18. Process Average - Raw Data**

<table>
<thead>
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<th>A1</th>
<th>B2</th>
<th>C1</th>
<th>D2</th>
<th>E1</th>
<th>G1</th>
</tr>
</thead>
</table>

Process Average (Regular) for:

Equals 1056.75000 +/- 98.537000

(from 1155.28700 to 958.213.00)
Table 19. Process Average - Raw Data

<table>
<thead>
<tr>
<th>Process Average (Regular) for:</th>
<th>A2</th>
<th>B2</th>
<th>C1</th>
<th>D2</th>
<th>E1</th>
<th>G2</th>
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<td>Equals 978.25000 +/- 98.537000</td>
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Fig. 2. The approximate cost breakdown of body-in-white (Ref. 6).
Fig. 3 Automobile Door - Weight Reduction Scheme (Ref. 15)
CONVENTIONAL PROCESSING

1994 WINDOW FRAME RAIL SCRAP SAVINGS ANALYSIS

Fig. 4. Conventional Window Frame Coil Processing and Blank Geometry (Ref. 15)
LASER WELDED BLANK

Fig. 5 Laser Welded Window Frame Blank And Savings of Engineering Scrap Materials (Ref. 15)
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CENTER PILLAR INNER

ORIGINAL DESIGN  LASER WELDED BLANK  FINAL FORMED PART

Fig. 7 Laser Welding Of Center Pillar To Optimize Structure
Integrated side member by laser welded blanks

Blanking  Welding  Stamping

Welds

Fig. 8 The Optimized Blanks And Subsequent Processes For Body-Side-Frame Applications (Ref. 17)
Integrated side member blank

Fig. 9 The Laser Weld Length And Material Designation (Ref. 17)
LASER-SURFACE INTERACTION

Thermal Conduction

Melting

Vaporization

Plasma Production

Fig. 10 Steps Of Laser Beam Material Interactions
DEEP PENETRATION

Fig. 13 Laser Welding-Key-Hole Phenomena
KEYHOLE WELDING

LASER BEAM

HIGH PRESSURE VAPOR

LIQUID METAL

WELDING DIRECTION

RESOLIDIFIED WELD ZONE

UNTREATED SOLID

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Fig. 10 Schematics of High Speed Weld Defects
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Relationship between clearance of butt welding and thickness ratio
**Strength ratio**

\[ S : \text{Strength of welded sheet metal} \]

\[ S_0 : \text{Strength of unwelded sheet metal} \]

- **Thickness ratio** \( t/t_0 \)

**Relationship between thickness ratio and tensile strength**

*Fig. 22 Relationship Between Thickness Ratio And Tensile Strength (Ref. 6)*
Material: SPCC
Sheet thickness: 0.8 mm

Relationship between thickness ratio and deformation limit strain

Test sample
Welded bead
Scribed circle L = 6.35 mm l = eₓ

Deformation limit strain

Formable area

\( t/t₀ \)

Fig. 23 Strain Limit Of Welded Sheet Steel (Ref. 17)
Fig. 24 Schematic Diagram Of Laser Resonator

1. Discharge tubes (8x)
2. Radial compressor
3. Heat exchanger
4. Folding mirror (behind the door)
5. Power sensor, window (behind the door)
6. Electrode
7. Matching network
8. Resonator fundament
9. RF generator housing/screening

10. Gas supply (gas mix unit)
11. Gaswater connections
12. Cooler tube cooling
13. Vacuum pumps (2x)
14. Transportation lock (red)
15. Opening for beam
16. Head computer with interface connecting to supply cabinet
Fig. 25 A View Of The Laser Head

Schematic diagram and description:

1. Discharge tube (6x)
2. End mirror Ge concave
3. ZnSe window
4. Radial compressor (4x)
5. Heat exchanger (3x)
6. Folding mirror, adjustable
7. Folding mirror, fixed
8. Power beam
9. Laser beam
10. Scraper mirror
11. End mirror Cu convex
12. Shutter
13. Absorber
14. Electrodes
KEPLERIAN EXPANDER

Fig. 26 Keplerian Beam Expander
Fig. 28 Example Of Focussing Diagnostics With The LASERSCOPE UFF 100 On A Industrial CO₂ Laser At A Power Level of 5 kW; Isometric Projection Of The Intensity Distribution (Left) And Modified contour Representation (Right). The Contours Are Horizontal Sections Taken Through The Projected Intensity Distribution (Left Hand Diagram) With The 0% Position At The Highest Peak Value. Therefore The 20% Contour Is The Intensity Cross Section Of The Beam 20% Below The Peak Value. (Beam Radius 196μm; Maximum Intensity 7.9 x 10⁶ W/cm²; Measuring Window: 0.5 x 0.5 mm²)
Fig. 29 Erichsen test cup set-up
Fig. 36 Plasma Suppression Technique Which Directs Shield Gas To Conform Plasma In The Keyhole
Laser Power: 7.5KW
Focal Length: 200 mm
Focus Displacement: -6 mm

Fig. 33 Isometric Projection Of Intensity Profiles
Laser Power: 7.5KW
Focal Length: 250 mm
Focus Displacement: -6 mm

Fig. 34 Isometric Projection Of Intensity Profiles
Laser Power: 7.5KW
Focal Length: 250 mm
Focus Displacement: +6 mm

Fig. 35 Isometric Projection Of Intensity Profiles
Laser Power: 7.5KW
Focal Length: 200 mm
Focus Displacement: +6 mm

Fig. 36 Isometric Projection Of Intensity Profiles
Laser Power: 9kW
Focal Length: 250 mm
Focus Displacement: +8 mm

Fig. 38 Isometric Projection Of Intensity Profiles
Helium @ 3 Bar (Operating Pressure) and @ 20°C Operating Temperature

Fig. 41 Measurement Of Flow Rate Of Helium
Helium @ 3 Bar (Operating Pressure) and @ 20°C Operating Temperature

Fig. 42 Measurement Of Flow Rate Of Helium
Argon @ 3 Bar (Operating Pressure) and @ 20°C Operating Temperature
Argon @ 3 Bar (Operating Pressure) and @ 20°C Operating Temperature

6.35 mm Tube Diameter

Fig. 44 Measurement Of Flow Rate Of Argon
RS 10000 RF caustic shape of the Laser beam (comprising 75% of the total power)

Distance from the Output Coupler (mm)

Raw Beam Shape

Fig. 45 Raw (Uncoupled) Beam Shape At Various Positions
Beam Divergence of RS 10,000 with Telescope

d01=19mm, z01=-5m, Kf=0.076 mmrad

Position of Telescope
-14, -9, -7, -5, -2, 0, 2, 5

Fig. 46 The Beam Shape After The Telescope
Focused Laser Beam

\[ f = 250 \text{ mm}, \ 9\text{KW at work-piece} \]

Fig. 47 Focus Spot Size For Focal Length Of 250mm And 9KW Power At Workpiece
Focused Laser Beam
f=200 mm, 9KW at work-piece

Fig. 48 Focus Spot Size For Focal Length Of 200mm And 9KW Power At Workpiece
Focused Laser Beam

f=250 mm, 7.5KW at work-piece

Fig. 49 Focus Spot Size For Focal Length Of 250mm And 7.5KW Power At Workpiece
Focused Laser Beam

f=200 mm, 7.5KW at work-piece

Fig. 50 Focus Spot Size For Focal Length Of 200mm And 7.5KW Power At Workpiece
<table>
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<th>Telescope</th>
<th>d @ 30%</th>
<th>d @ 45%</th>
<th>d @ 60%</th>
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<tr>
<td>2.5</td>
<td>0.93</td>
<td>0.92</td>
<td>0.95</td>
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<tr>
<td>5</td>
<td>0.64</td>
<td>0.63</td>
<td>0.68</td>
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<tr>
<td>10</td>
<td>0.39</td>
<td>0.44</td>
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$d =$ mm

**Variable Distance Between Focusing Telescopic Optics (mm)**

Fig. 51 The Influence Of Telescope Adjustment Of On Focus Spot Size
Fig. 52 Quasi - Periodic instability of surface perturbation (above (a)- top weld bead, below (b) bottom weld bead)
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Fig. 53 Quasi-Periodic instability or surface perturbation (top weld beads).
Experimental Conditions, Bead-On-Plate- Experiment 1
Fig. 54 Quasi - Periodic instability or surface perturbation (top weld beads)
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Fig. 59  The Deformation Of Welded Specimens Of Erichsen Cup Test, Where Penetrator Was Faced Towards Top Weld Bead (Laser Butt Welding Experiment-30)
Fig. 60 The Deformation Of Welded Specimens Of Erichsen Cup Test, Where Penetrator Was Faced Towards Bottom Weld Bead (Laser Butt Welding Experiment-31)
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(Arrow Shows Penetrator's Direction)
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(Arrow Shows Penetrator's Direction)
Fig. 64 The Metallography Of Erichsen Test Samples Which Employed Parameters Of Experiment-32
(Arrow Shows Penetrator's Direction)
Fig. 65 The Metallography Of Erichsen Test Samples Which Employed Parameters Of Experiment-33
(Arrow Shows Penetrator's Direction)
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(above (a.) top weld bead, below (b.) bottom weld bead)
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(above (a.) top weld bead, below (b.) bottom weld bead)
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(above (a.) top weld bead, below (b.) bottom weld bead)
Fig. 70 Optical microscopy of weld samples of Taguchi - Experiment 5
(above (a.) top weld bead, below (b.) bottom weld bead)
Fig. 71 Optical microscopy of weld samples of Taguchi - Experiment 6
(above (a.) top weld bead, below (b.) bottom weld bead)
Fig. 72 Optical microscopy of weld samples of Taguchi—Experiment 7
(above (a.) top weld bead, below (b.) bottom weld bead)
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(above (a.) top weld bead, below (b.) bottom weld bead)
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Load vs. Displacement - IF 18 Unwelded

Fig. 81 Tensile Plots Of Unwelded Specimens
Load vs. Displacement - Experiment #3

Fig. 84  Tensile Plots Of Welded Specimens
Load vs. Displacement - Experiment #4

Fig. 85 Tensile Plots Of Welded Specimens
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Load vs. Displacement - Experiment #7

Fig. 88 Tensile Plots Of Welded Specimens
Fig. 69 Tensile Test Of Welded Specimen
STAGES OF BEAM-MATERIAL INTERACTIONS

Radiation

Absorption → Reflection

Heating

Melting

Surface Depression

Surface Tension → Flow

Heating

Vaporization → Material Removal

Keyhole

Perturbation → Plasma → Radiation

Material Properties T, K, C, K

Fusion

Fig. 90 Basis Of Material Interactions In Laser Welding
LASER WELDING

Fig. 91 Keyhole And Its Environment
Weld Penetration

\( Z \) Weld Penetration
\( \Delta Z \) A wave height propagating with velocity \( v \)
\( v \) Weld Speed

Fig. 92 Cross-Section Of Keyhole Showing All Associated Phases
Non-Inertial Frame of Reference

$Z$ Weld Penetration

$\Delta Z$ A wave height propagating with velocity $v$
Fig. 97 An Inertial Frame of Reference
Laser Weld Study Optimization

Fig. 98 Average Process Response
Laser Weld Study Optimization
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Fig. 124: Weld boundaries measured from photomicrographs of Taguchi: Experiment 5
Fig. 127 CAD reconstruction of laser weld Taguchi- Experiment 5
APPENDICES
### APPENDIX A  R-S 10000 Specifications

**Type of laser:** RS 10000 RF

**Cooling water:**
The cooling water connections are located at the connection wall of the laser head. The connections are provided for plastic hoses 1 1/4" and 1". They are plugged on and secured by hose clamps.

**Gas cooling circuit** (four 1 1/4" connections, two inlets and two outlets):
- **Flow:** 2 x 160 l/min min.
- **Input pressure:** 5000 - 7000 hPa (5 - 7 bar) max.
- **Pressure drop in laser:** 4000 hPa (4 bar)
- **Cooling capacity:** 2 x 100 kW
- **Water quality:** refer to section 3.2.4
- **Contaminations:** ≤ 50 μm
- **Temperature:** 15°C to 25°C (above dew point!)

**Recommended temperature:** 18°C to 20°C
If you do not want to use the recommended cooling water temperature, the laser has to be readjusted to this temperature by the ROFIN-SINAR service!

**Temperature constancy:** ΔT ± 0.5°C

**Optics cooling circuit** (1" connections):
- **Flow:** 80 l/min min.
- **Input pressure:** 3500 - 4000 hPa (3.5 - 4 bar) max.
- **Pressure drop in laser:** 3000 hPa (3 bar)
- **Cooling capacity:** 5 kW
- **Water quality:** refer to section 3.2.4
- **Contaminations:** ≤ 50 μm
- **Temperature:** 20°C to 30°C (above dew point!)

**Temperature constancy:** ΔT ± 0.5°C

---

**Compressed air:**
- **Consumption:** approx. 0.1 Nl per shutter opening
- **Quality:** water-free, filtered, permissible filter pore width: ≤ 5 μm
- **Pressure:** 4500 to 6000 hPa (4.5 to 6 bars)

(all pressure specifications refer to atmospheric pressure)

**Ambient conditions:**
- **Temperature:** 10°C to 40°C with constant warming up
- **Relative air humidity:** depending on ambient temperature and cooling water temperature. The dew-point temperature resulting from relative air humidity and ambient temperature must be clearly below cooling water temperature to prevent condensation on the optics.

**Place of installation:** before running the laser in altitude levels above 1000m please contact ROFIN SINAR.
### Specifications:

<table>
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<th>Type of laser:</th>
<th>RS 10000 RF</th>
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<tr>
<td>Beam data:</td>
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<tr>
<td>Wave length:</td>
<td>10.6 μm</td>
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<tr>
<td>Excitation:</td>
<td>RF 28.5 ± 1 MHz</td>
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<tr>
<td>Output:</td>
<td></td>
</tr>
<tr>
<td>Guaranteed:</td>
<td>10000 W</td>
</tr>
<tr>
<td>Range (typ.):</td>
<td>2000-12000 W</td>
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<tr>
<td>Stability:</td>
<td>± 2 % long time (cooling water ΔT ± 0.5° C)</td>
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<tr>
<td>Beam quality:</td>
<td></td>
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<tr>
<td>Diameter:</td>
<td>approx. 46 mm</td>
</tr>
<tr>
<td>Divergence:</td>
<td>≤ 1.5 mrad full angle (up to 10 m; for values for distances &gt; 10 m, please contact ROFIN-SINAR)</td>
</tr>
<tr>
<td>Pointing stability:</td>
<td>≤ 0.15 mrad</td>
</tr>
<tr>
<td>Beam quality:</td>
<td>K ≥ 0.2</td>
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<tr>
<td>Polarization:</td>
<td>linear, 45° relative to the horizontal plane</td>
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### Dimensions:

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<th>Laser head:</th>
<th>(L) 4650 mm</th>
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<tr>
<td>(W) 1450 mm</td>
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<tr>
<td>(H) 2910 mm</td>
<td></td>
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<tr>
<td>Supply cabinet:</td>
<td>(L) 6140 mm</td>
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<tr>
<td>(D) 630 mm</td>
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<tr>
<td>(H) 2655 mm</td>
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### Weight:
- Laser head: approx. 7300 kg
- Supply cabinet: approx. 2900 kg

### Possibilities for external control:
- CNC interface:
  - Commands from external control panel
  - Messages for external control
  - Externally controllable pulse interface
  - Externally controllable analog signals
  - Ramping generator

### Electric connection:
- The power supply has to be prepared by the customer.
- Voltage: 400 V AC (+5 %, -10 %)
- Other operating voltages possible by means of series transformer (option)
- 50 or 60 Hz, 3 phases, PE
- Frequency has to be defined prior to the production of the laser

### Laser gas consumption:
- He: 190 N/h, purity 4.6
- N₂: 65 N/h, purity 4.6
- CO₂: 10 N/h, purity 4.5

### Typical current consumption at rated output capacity:
- 170 kVA, 159 kW, cos φ = 0.93
- Max. current consumption: 210 kVA
- Current consumption: 300 A max.
- Fuses: 400 A slow-blow

### Voltage:
- 230 V AC, ± 6 %, ± 10 %, 50 or 60 Hz, 1 phase, N, PE, 16 A slow-blow fuse for service sockets and cabinet lighting
APPENDIX B - FROUDE NUMBER AND OPEN-CHANNEL HYDRODYNAMICS

The open-channel flow can be classified by dimensionless parameter Froude number. Froude number is named after William Froude, a British Naval Architect who proposed similarity rules for free surface flows such as surface waves, open-channels. The Froude number is the dominant effect only in free surface flows and is unimportant if there is no free surface. The physical significance of the Froude number, \( F_r \), is that it is a measure of the ratio of inertial to the gravitational forces.

Depending on the magnitude of the ratio of inertial to gravitational forces, an open-channel flow can be classified as subcritical, critical and supercritical. The parameter on which these classifications are based is known as Froude number, \( F_r \), and is defined by

\[
F_r = \frac{v_o}{(gz)^{1/2}} \quad (B.1)
\]

where \( v = \) a characteristic velocity of flow, \( z = c \), characteristic length. In an open-channel flow, a characteristic length is usually the "hydraulic depth". The hydraulic depth is defined as the ratio of flow area \( a \) and the width of the free surface, \( w \), or

\[
z = \frac{a}{w} \quad (B.2)
\]

Now the three flow regimes are:

\[
\begin{align*}
F_r &< 1.0 \quad \text{Subcritical Flow} \\
F_r &= 1.0 \quad \text{Critical Flow} \\
F_r &> 1.0 \quad \text{Supercritical Flow}
\end{align*}
\]
If \( F_r = 1 \), the flow is in a critical state where the inertial and gravitational forces are in equilibrium. If \( F_r < 1 \), the flow is in a subcritical state, and the gravitational forces are dominant. If \( F_r > 1 \), the flow is in a supercritical state and the inertial forces are dominant. The velocity of flow of a surface perturbation or surface wave is given by equation (9.24).

\[
\nu = (gz \left( 1 + \frac{\Delta z}{z} \right) \left( 1 + \frac{\Delta z/2}{z} \right)^{1/2})
\]

(9.24)

In the limit of an infinitesimal perturbation, the velocity becomes

\[
\nu_o = (gz)^{1/2}
\]

(9.26)

The flow is at a critical state, because the denominator of the Froude number is also \((gz)^{1/2}\). When the flow is subcritical, the surface wave can propagate upstream. When the flow is supercritical, a surface wave cannot propagate upstream against the flow. In subcritical flow, the upstream areas are in hydraulic communication with the downstream areas, whereas, for a supercritical state the upstream is in hydraulic discontinuity with the downstream areas of the fluid flow.
APPENDIX C - GLOSSARY OF TERMS

**Autogenous:** A term used for welding process that does not require addition of materials such as filler wire, powder, etc.

**Bead-on-plate:** A term used in laser and electron beam welding where weld bead is placed on material substrate not on any kinds of joints.

**Beam Delivery System:** The use of optical components, such as mirrors and lenses, arranged and aligned in such a way that a laser beam can be precisely positioned to a work-piece location.

**Beam Expander:** An optical device that recollimate the beam.

**Body-in-white:** A term for the metal shell of the automotive vehicle body including the doors and deck lids prior to paint and trim.

**Design Capability Index (C_{pk}):** It is a measure of how well a manufacturing process can produce parts that meets specification, high \( C_{pk} \) means higher percentage of parts are produced within the specification.

**Tailored Welded Blanks (also called tailored blanks):** An optimized material sheet which is produced by welding of different material sheets, each having only the properties for its particular location.
SIGNIFICANT CONTRIBUTIONS
OF THIS RESEARCH

The following significant contributions and advancement of knowledge have been made in this research:

- Experimental solutions have been provided for high speed bead-on-plate welding.
- Experimental observations were made of surface characteristics at different welding speeds and transition to instability.
- Experimental values for high speed butt welding were found.
- A Taguchi analysis of laser welding process parameters for butt welding have been developed.
- A mathematical model has been developed to describe instability at high welding speeds.
- Dynamic similitude to establish stability and instability criteria making use of the Froude number has been developed.
- Experimental values have been measured for instability at high welding speeds.
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<th><strong>Name</strong></th>
<th>M. Nasim Uddin</th>
</tr>
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<tbody>
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<td><strong>Place of Birth</strong></td>
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<tr>
<td><strong>Year of Birth</strong></td>
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<tr>
<td><strong>Education</strong></td>
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<td><strong>Experience:</strong></td>
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