Optimization of Parameters for Effective Laser Welding of Aerospace Components

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Abstract

This paper reports research results in two areas. First, it defines laser-welding processes for jet engine turbine components and specifies the steps and parameters for that process. Secondly, it proposes an optimization routine aimed at finding optimum welding procedures and parameters since laser welding is not commonly used in aerospace applications. This paper proposes guidelines for laser welding of nickel-alloy sheet metal up to 0.061” in thickness. These guidelines are based in part on processes previously reported in the literature including comparisons with conventional welding technologies.

One area where laser welding may prove advantageous is in improving the cost and quality of combustor component manufacturing. The results of a feasibility study of laser welding including quality, material integrity, and economic benefits are included. Recommendations in the area of design guidelines to maximize the benefits of laser welding in the manufacturing process are provided. This paper reports on the use of a fiber optic laser for welding using three control factors: optical power, welding speed and minimum spot diameter for an Inconel 625 sheet. Using a Taguchi design of experiment model, laser weld outcomes are analyzed and optimal weld porosity results are reported.

Introduction

Inconel 625 is a nickel-based super alloy widely used in aerospace jet engines because of its high corrosion resistance and high temperature characteristics. Laser welding of Inconel super alloys has been an area of commercial development in recent years [1, 2]. Laser joining, especially laser welding process has improved the cost and manufacturing quality of combustor components. (Figure 1).

There are a number of fusion welding processes appropriate for joining heavy sections [3, 4]. Among these are: gas tungsten arc welding (GTA), shielded metal arc welding (SMAW) and electron beam welding (EBW). Laser beam welding (LBW) is a competing process that offers precise, low heat input that is well-suited to manufacturing. Figures 2 and 3 show a laser welder, YLR 1700-WC at IPG (Oxford, Mass.).

Figure 1 Jet engine combustor component

Figure 2 YLR 1700-WC

Figure 3 YLR laser head

A laser produces an intense beam of optical energy within a narrow wavelength band. Using a focusing lens, this beam can easily be shaped for minimum divergence and spot size prior to impinging the work-piece [5]. The work-piece and laser beam are independently manipulated by multi-axis robotics. When absorbed by the surface of the work-piece, the laser provides the heat source for the welding process. The focused spot size can be adjusted to varying sizes from 0.004" to 0.040". The smaller size is used for cutting, drilling and welding and the larger, for heat treating [6].

Functional Specification

The specific weld joint under consideration is part of a fabricated combustor liner assembly in a jet engine turbine used in military aircraft. An important function of the sheet metal assembly is to seal mating combustor liner segments. Cooling air passes through the sheet metal assembly and impinges on the liner segments. This air must be captured in a pocket formed by the sheet metal and the combustor liner segment [7]. The liner segments are investment cast pieces approximately two inches in width with a length spanning a 40-degree arc segment of a 30" diameter loop. They are attached to the sheet metal with threaded fasteners. The sealing is simply metal-on-metal since it is in the 'hot section' of the engine. Distortion from welding must be less than 0.005" on line elements cut through the conic section. On a weld joint with two rings, the surfaces must be aligned within the aforementioned tolerance, and the entire surface must lie within that zone. No peaks or shallow locations from weld shrinkage are allowed. The weld must be finished flat to within 0.005" on the mating surface and have no under fill on the opposite side [8].

The stress on both the circumferential and radial welds is relatively low during subsequent manufacturing operations and even engine operation. Even so, no visible defects or cracking is allowed. The entire assembly is subject to a high temperature solution heat treat after welding is completed. The welds are expected to last the life of the engine, up to 50,000 hours. The burner shell assembly is not a normally a serviced part during engine overhaul, but is repaired as required when removed during a normal overhaul [9].

The subassembly is spun formed and trimmed to the proper length as the last operation. Both end faces must be perpendicular to the centerline axis within 0.020". The geometry and true position of the axes and end faces must remain in the proper position after welding Figure 5.

The type of weld currently being used is a butt joint which is an excellent candidate for laser welding. The laser beam is aligned to impinge straight along the mating edges of the materials to be joined. Since the laser beam is focused in a narrow area, the gap between the mating surfaces must be in the order of $1/20^{th}$ of the spot size diameter. The resulting gap should be less than 0.001" which is achievable since both parts are trimmed while on the forming fixture. A welding fixture is used to constrain the rings and provide a modest axial force that pushes the mating faces together. Weld shrinkage allowance has been considered in the axial direction only. Further refinement is needed based on additional laser weld process experience.

Optimization Techniques

In laser welding, a number of parameters may be varied to achieve an optimized and robust welding process. Since laser welding is an automated process, some parameters can easily be controlled, e.g. optical power, focal position, welding speed, shielding gas type and volume. Other parameters can be changed but require equipment modifications, e.g. laser wavelength, split beam welds and focused spot size. Surface and joint preparation can also be optimized through machining, and preparation changes without any additional change or investment to the laser equipment. Optimization based on these parameters defines the welding procedure and is normally done in relation to what is a “good” as opposed to a “bad” weld. This determination involves sectioning welds to measure cross-sections and shapes as well as metallurgical and micro-structural properties. Mechanical testing is also used to define the range of acceptable welding outcomes.

Research Methodology

In its early years, laser welding was used mainly in applications where no other welding processes were suitable. Today, laser welding is an integral part of the welding industry, regularly producing welds for a myriad of components. Nonetheless, some manufacturing engineers do not seriously consider laser welding as an alternative. Some reasons are: unfamiliarity with the operation and its capabilities, relatively high initial costs, and concerns with safety in a manufacturing environment.

Laser welding is a viable alternative to many aerospace processes, such as resistance welds (spot or seam), submerged arc, RF induction, high-frequency resistance, ultrasonic and electron-beam. While each of these techniques has established an independent niche in manufacturing work cells, laser welding is a viable economic alternative. In some cases, the welding system can be used to perform other functions, such as cutting, drilling, scribing, sealing and serializing [10].

Industry observers state that there are currently 2,000 laser machine tools in use for cutting, welding and drilling. That the number is forecasted to reach 30,000 over the next 15 years as manufacturing engineers become more aware of the capabilities of lasers. The flexibility of lasers to supply energy to hard-to-reach spots, vary their output energy over a wide range, and inject a minimum of heat into a part makes them ideal for many flexible manufacturing operations.

To appreciate the potential of laser welding, one must re-define the traditional approach to viewing energy conversion ‘efficiency’. The laser is a relatively inefficient converter of electrical energy to optical output, with the best lasers yielding 2 to 15 percent energy conversion. However, most of this output energy can be delivered to a spot size of a few thousandths of an inch [10]. As a result, lasers efficiently apply thermal energy to small areas better than conventional welding.

Being able to select and vary the optical energy offers some distinct metallurgical advantages; narrow heat affected zone due to minimum heat input on welded metal. However, since the surface heating generated by the optical energy relies on the material's heat conductivity to produce the weld, penetration is usually limited to less than 2 millimeters [11]. Using a technique known as keyholing, higher power lasers ($>10E6\ W/cm^2$) can make deeper penetrations. The major benefit of keyholing is a faster weld speed, and thick material can be welded with one pass from only one side of the joint.

The amount of energy put into the metal per unit length of weld line is called the energy input and is computed as follows:

$$H = \frac{P}{V} \qquad (1)$$

Where H = energy input in J/mm
P = total absorbed optical power in watts
V = travel velocity in mm/s

If a laser beam of absorbed power P is focused to a spot of diameter d, the irradiance (often referred to as the power density) is:

$$PD = \frac{P}{\left(\frac{\pi d^2}{4}\right)} \qquad (2)$$

Where PD = power density in watt/mm^2
P = absorbed optical power in watts
d = focused spot size in mm

Within the industry, irradiances are usually reported in units of W/cm^2 even though this is not an SI unit.

Metals are generally very good reflectors of light. This problem is compounded by the fact that most industrial lasers emit infrared light, which metals reflect even better than visible light. As a result, most of the incoming optical energy is reflected. Since metals are also good conductors of heat, the power that does perform useful work is rapidly conducted away from the spot being heated. The actual amount of energy absorption can be determined as follows:

$$\eta_l = 0.365\left[\frac{r}{\lambda}\right]^{1/2} - 0.0667\left[\frac{r}{\lambda}\right] + 0.006\left[\frac{r}{\lambda}\right]^{3/2} \qquad (3)$$

Where ηl = absorptivity at temperature, T, fraction
r = resistivity, ohms-m
λ = wavelength, m

A typical range of energy absorbed is 10-20% of the incident optical radiation. Note that the wavelength of the laser has a large affect on the amount of energy absorbed, so the smaller the laser wavelength, the better the absorption of energy into the metal.

By heating a spot on the work-piece above the boiling point of the metal, a vaporized hole is formed. It is filled with ionized metallic gases that are an effective absorbent, trapping about 95 percent of the laser energy into a cylindrical volume, known as the keyhole. Temperatures in the keyhole can reach as high as 25,000°C making this technique very efficient [10].

Instead of heat being conducted mainly downward from the surface, it is conducted radially outward from the keyhole forming a molten region around the vapor [11]. Some of the light is absorbed by the vapor, while the rest reflects multiple times inside the channel and delivers some energy on each reflection. The keyhole technique allows lasers to produce welds that are deep and narrow. The aspect ratio (depth/width) of keyhole laser welds can be as high as 8:1 but are more commonly around 4:1.

At irradiances above 10E6 W/cm2, the above events occur within a microsecond in materials such as steel. Keyhole welding is a threshold process and when the irradiance is low, very little power is absorbed. Once the irradiance is high enough to form a keyhole, most of the power is absorbed into the work-piece. Small power changes near the keyhole threshold can cause dramatic changes in the welding process.

When the laser beam moves along the work-piece, molten metal fills in behind the keyhole and solidifies to form the weld. This technique permits welding speeds of hundreds of centimeters per minute depending on laser size [12]. Adjacent to the weld metal is the heat-affected zone (HAZ), the portion of the base metal that is not completely melted, but whose microstructure or mechanical properties have been altered by the heat. The width of the HAZ is a function of the heat input which varies with different welding processes as well as the parameters of the process.

The HAZ is also where distortion takes place. With laser welding, the low total heat input results in almost no distortion. Lower heat input has other benefits, such as being able to use fixtures that do not need to withstand large thermal expansion forces or to act as heat sinks. The width of the HAZ can be found once the heat input has been determined, using the material properties of the work-piece. Using the following formula, one can find the peak temperature at a distance from the weld.

$$\frac{1}{T_p - T_o} = \frac{\sqrt{2\pi e}\rho ChY}{H_{net}} + \frac{1}{T_m - T_o} \qquad (4)$$

Where T_p = peak temperature in ºC
T_o = initial plate temperature in ºC
T_m = melting temperature of material in ºC
ρ = density in kg / mm^3
C = specific heat in J/kg-K
h = thickness in mm
Y = distance from fusion area to T_p edge
H_{net} = heat input in J/mm

Chemical reactions, such as oxidation or nitrating with atmospheric gases at high temperatures can pose problems. This is particularly true when the oxides or other elements formed have disassociation temperatures far above the melting point of the metal. The result is brittle, porous welds. Covering the welding area with an inert gas such as argon or helium minimizes these reactions in most cases. For some materials, it is necessary to perform the welding in a sealed chamber to prevent outside contamination.

Economic Factors

A key determinant in choosing a welding technology is return-on-investment (ROI). One means to create an acceptable ROI is to minimize labor costs through automation. This is particularly true in the aerospace industry where cost and performance advantages are keys to future business. One example is shown in Figures 4-6 that provide a detailed progression from the turbine engine to a welded area on the combustor.

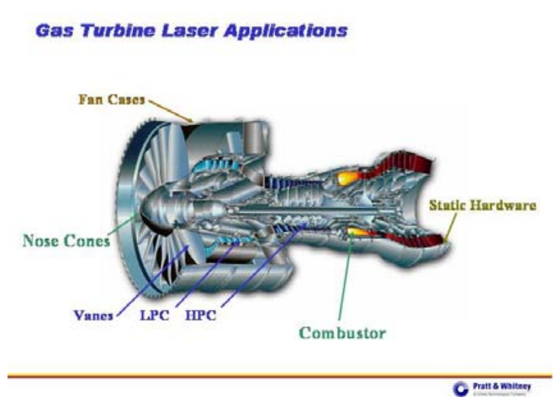


Figure 4 Gas turbine laser applications

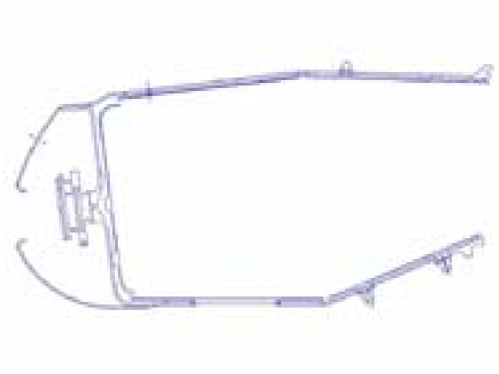


Figure 5 Combustor x-section

Figure 6 Welded area on combustor

Over time, laser welding processes have gradually supplanted traditional manual welding operations. Most manufacturing engineers have read about the advantages of laser welding over more conventional techniques. So, why has the adoption rate by manufacturing industries not been faster [13, 14]? A likely cause is that the industrial user sees no benefit from publicizing the cost savings realized with a laser welding system. Most manufacturers treat their usage of lasers as proprietary.

Evaluating Laser Welding Systems

The most popular lasers being used for welding are CO_2 and Nd: YAG or Nd: Glass. The CO_2 laser uses a combination of carbon dioxide, helium and nitrogen. This gas mixture circulates through a bank of electrodes, which is the energy source. CO_2 lasers have been developed with outputs as high as 25 kilowatts. This high output is possible since the CO_2 gas mixture can be efficiently cooled. An Nd: YAG laser, by contrast, emits from a neodymium-doped yttrium aluminum garnet crystal. Cooling the crystal is critical and difficult which limits its maximum output power to several thousand watts.

Nd: YAG lasers have found widespread application in the electronic/electrical industries for spot welding and beam lead welding of integrated circuits. One advantage of Nd: YAG or solid state laser is its ability to transmit the beam down a fiber optic cable allowing easier manipulation of the beam to remote and complex locations, e.g. the end of a robotic arm. Figure 7 shows the compact size offered by a fiber delivered laser welder.

Figure 7 Fiber-delivered laser welder

Fiber lasers show great promise for wide range of application because they are truly solid-state with a minimum of exposed optical interfaces, have very high efficiency and are capable of excellent beam quality. The gain medium in fiber laser is based on a Yb, Nd, or Er-doped core in an optical fiber. Both the pump and signal beams propagate along the length of the fiber. Advantages of fiber lasers over other laser technologies are (12):

1. High electrical-to-optical efficiency (39%), an order of magnitude higher than conventional solid-state lasers
2. High-gain (50 dB) and low-threshold operation
3. Diffraction-limited beam quality that is insensitive to thermal or mechanical fluctuations, optical power level, or aging of the laser system.
4. Continuous tunability
5. Broad wavelength coverage in the near-IR by selection of various rare-earth dopants
6. Pumping with low-cost, reliable diode lasers
7. Low heat dissipation and facile thermal management
8. Scalable to high power
9. Efficient nonlinear conversions to visible and ultraviolet wavelengths

Quality Evaluation

Weld quality relates directly to the integrity of the weldment, and also includes design considerations. Each weldment should be:

1. Adequately designed to meet the service life.
2. Fabricated in accordance with design standards.
3. Operates within stress, fatigue, and corrosion limits.

Both economic and safety considerations influence weld quality. Economic considerations require that a product be competitive in the market, while safety requires that the product function without being a hazard to people or property. The safety aspect is by far the primary goal in the aerospace field. Cost is important, but quality is paramount.

The term used to describe a defect in a weldment is a discontinuity. A discontinuity is an “interruption of the typical structure of a material, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics” [18]. Discontinuities commonly associated with laser beam welding are: porosity, incomplete fusion, incomplete joint penetration, and cracks. Quality problems can often be traced back to the base material; however, in the aerospace industry, all material must be flight quality certified prior to use. The base metal used in this study has been recommended by an aerospace engine manufacturing company.

Experiments Performed

The welding tests were carried out on Inconel 625 coupons 0.061 inch thick. Using fiber laser (YLR 1700-WC), operating in continuous wave, with maximum out power of 3 kW. The fiber diameter was 100 microns with a collimator focal length of 83 mm. The beam was focused on the surface of the work-piece for all test runs, and all samples were shielded by a coaxial flow of helium.

A series of bead-on-plate welds were performed on 3” x 2” Inconel 625 coupons. They were performed by varying key process parameters: optical power, welding speed and the spot diameter. The Taguchi method was used to design the parameter matrix. A nine element orthogonal array with three levels of control was used as shown in Tables 1 and 2.

Experiment Reference	Power (watt)	Speed (in/min)	Spot size (µm)	Porosity (mm^2)
A	1	1	1	0.041587
B	1	1	2	0.153369
C	1	1	3	0.056748
D	2	2	1	0.153369
E	2	2	2	0.016625
F	2	2	3	0.098757
G	3	3	1	0.016735
H	3	3	2	0.020143
I	3	3	3	0.039247

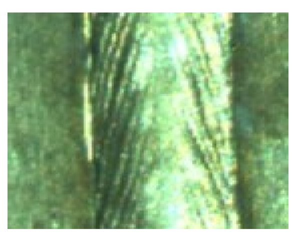
Table 1 Nine-element parameter matrix

Control Factor	**Level 1**	**Level 2**	**Level 3**
Power (watts)	500	700	900
Speed (in/min)	100	150	200
Spot size (µm)	100	150	200

Table 2 Control factor levels

Pictures of the laser welds for each of the nine experiments are shown in Figures 8-A through 8-I.

A



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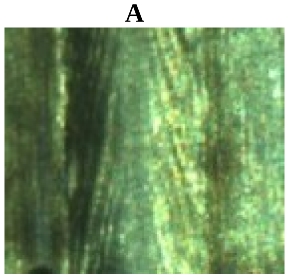

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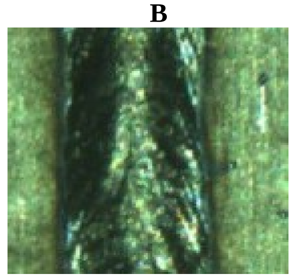

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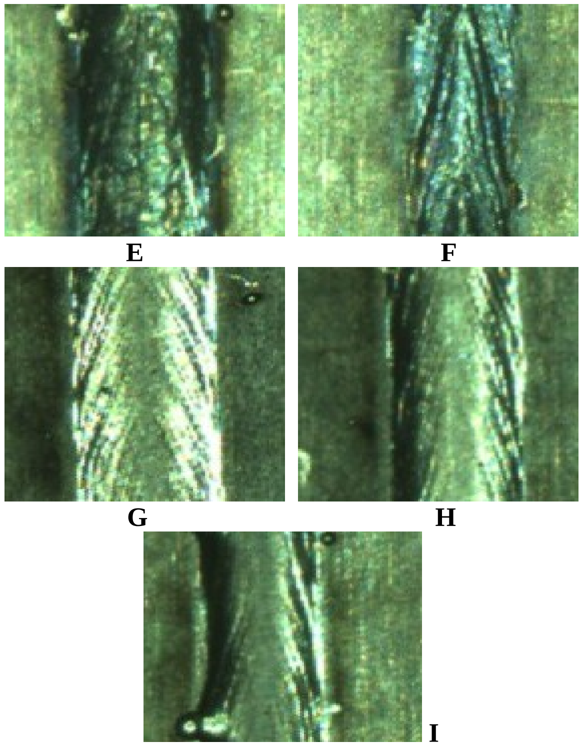


I

Figure 8 Photographs of laser welds

The optical power, speed and spot sizes used in the nine experiments are shown in Table 2, the control factors levels were obtained by using laser welding software SOAR 'Sandia Optimization and Analysis Routines.

Material Composition

The chemical composition of Inconel 625 is shown in Table 3.

Nickel	58.0 min.
Chromium	20.0-23.0 max.
Iron	5.0 max.
Molybdenum	8.0-10.0
Niobium (Plus Tantalum)	3.15-4.15
Carbon	0.10 max.
Manganese	0.50 max.
Silicon	0.50 max.
Phosphorus	0.40 max.
Sulfur	0.015 max.
Aluminum	0.40 max.
Titanium	0.40 max.
Cobalt	1.0 max.

Table 3: Chemical Composition of IN 625

Samples Preparation

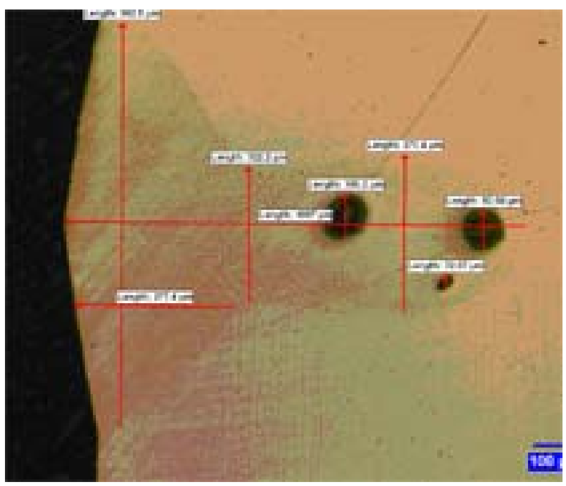
A 0.12 inch diamond blade (Leco) was used in a small automated cutoff machine (Struers Accutom) to make cross sectional cuts across each laser weld. The pieces containing the welds in cross section were then hot mounted using powder mounting compound (Buehler Epomet) and a mounting press (Leco PR-30).

Rough and fine grinding was performed using silicon carbide paper at decreasing grit size from 320 to 4000. Polishing was performed using suspensions of six, three, and one-micron diamond at approximately 5 minutes per step. An etchant containing 15 mL HCl, 10 mL acetic acid, and 10 mL nitric acid was used to reveal the weld microstructure [20]. This etchant was swabbed across the mounted sample with a cotton tip for approximately 30 seconds or until a reaction was initiated.

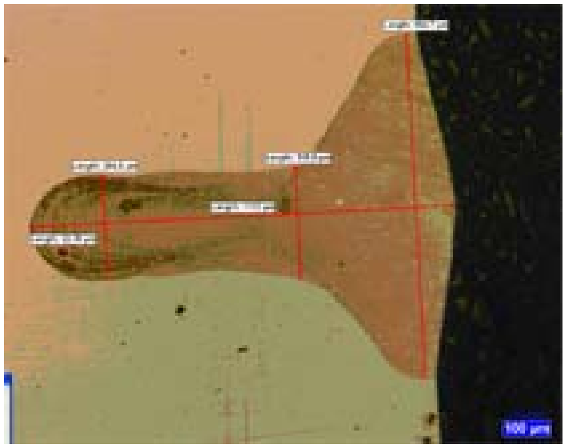
Results

In the Taguchi method, the factors that affect the mean and the variation in the process for a series of designed experiments are investigated. Using an orthogonal array design, variations caused by environmental and/or uncontrollable factors are minimized. Control factors are those that within the experiment can easily be set and held relatively constant. Noise variables are factors the experiment either overlooks or chooses not to control directly.

It has been previously reported that Inconel has a tendency towards porosity when laser-welded. In some of the microstructure pictures, we noticed the presence of porosity as well. Figures 9-a through 9-f show pictures of six weld cross-sections including labeling and measurement of the porosity defect sites.



a



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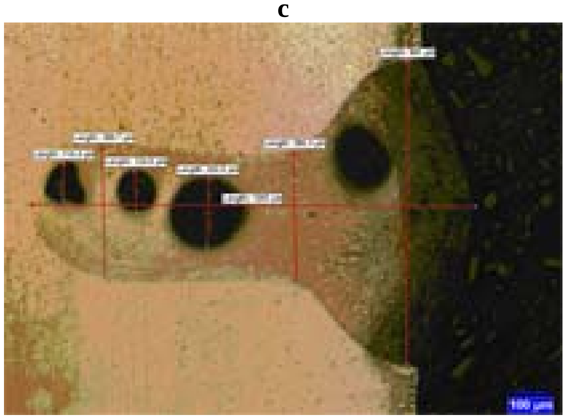

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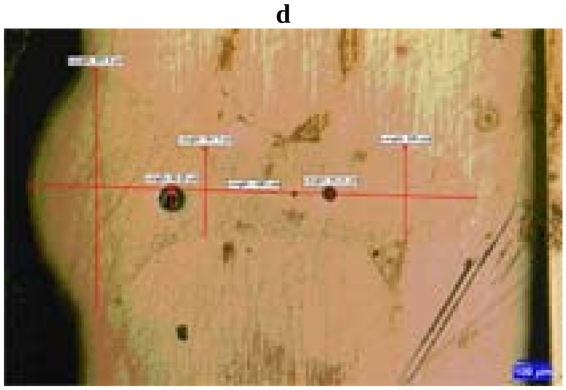

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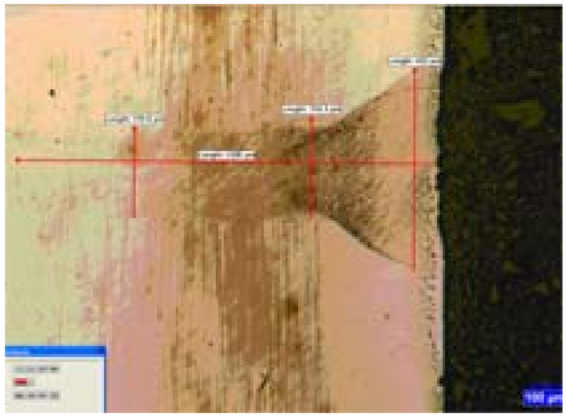

f

Figure 9 Photographs of weld cross-sections

The results were analyzed using the statistical software MINITAB [17]. Figure 10 shows the optimum combination for the control factors studied.

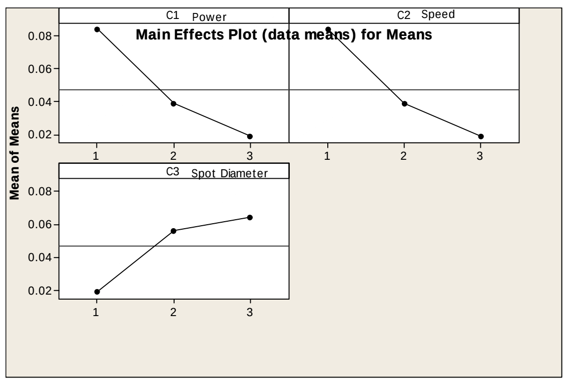

Figure 10 Optimal values for the control factors

S/N ratios measure the effect of the noise, and the results are shown in Figure 11. The higher values for the control factors indicate less sensitivity of defect to noise factor.

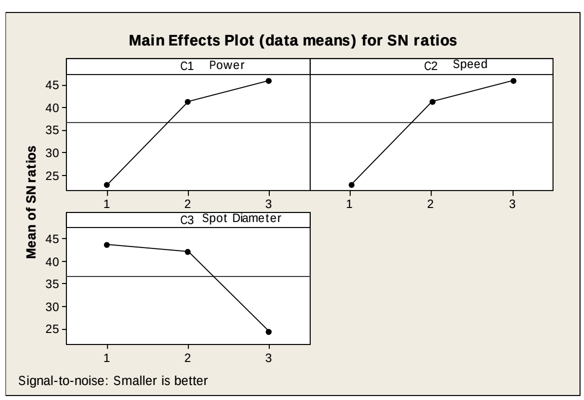

Figure 11 S/N ratios for the control factors

After analyzing these results, the combination and levels for the control factors that minimize weld porosity is shown in Table 5. These same values also maximize the insensitivity to the noise factors.

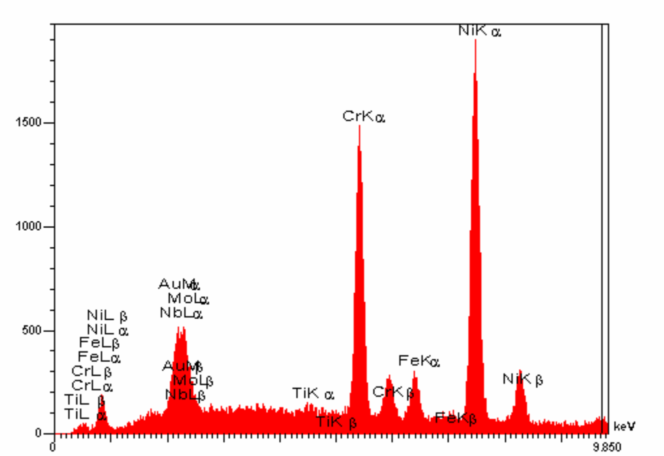

Figure 12: Spectral Analysis of the Base Metal

Defect	Power	Speed	Spot Diameter
Porosity	3	3	1

Table 5 Optimal control factor levels

Energy Dispersive Spectroscopy (EDS)

Elemental analysis was carried out in using an energy dispersive spectroscope mounted on a SEM. The base metal and the weld area of the sample shown in Figure 9d were analyzed. The gold peak shown in the EDS output is the coating material and not part of the metal itself. The percent area occupied by each elemental peak is shown in Figure 14. As it is obvious from the EDS output and Figure 14, there is not much discernable difference between elemental composition of the base material and the weld area. The crystalline structure of the metal in weld area has not been affected appreciably by heat treatment as a result of weldment.

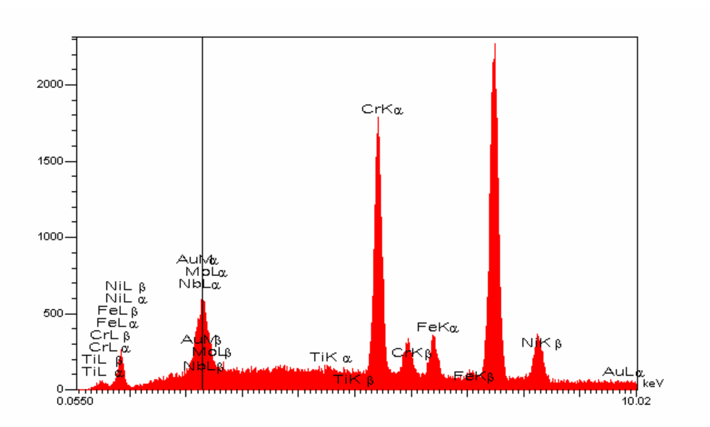

Figure13: Spectral Analysis of the Weld

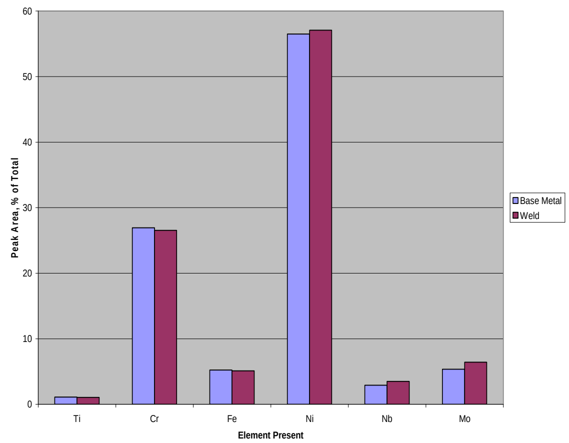

Figure 14: Peak intensity

Conclusions

The work described in this paper was aimed at developing a procedure for optimizing the laser parameters for welding applications in aerospace industry. A combination of welding software and Taguchi method used in this study to design and determine the optimum set of parameters required for laser weld application. Metallographic work revealed the weld defects on the welded samples and the results were analyzed by statistical software MINTAB. Scanning Electron Analysis for the weld and the parent material proof that the weld has not lost the alloying elements which is gives laser weld advantage over conventional procedures especially for the combustor part which is undergoing heat treatment after the weld is performed.

The expanded use of laser welding in the aerospace industry must address perceptions of both cost and manufacturing compatibility. Capital investment is an issue for any industry when deciding on a manufacturing method. Maximizing hours on the equipment as soon as it is put into service can justify the cash outlay and show a return on investment.

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