MODELLING OF Nd-YAG CONTINUOUSLY LASER WELDING PROCESS OF TI-6Al-4V AND X5CrNi18-10 USING FACTORIAL DESIGN

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Abstract

The welding of titanium alloys having a α + β structure with austenitic stainless steels can not be done directly by a melting process, due to the appearance of intermetallic phases in the mixing of the molten materials that promotes the cracking phenomena. Changing the chemical composition of the molten bath is the only way to obtain a melt joint directly. The purpose of this paper aims the modelling of the main process parameters of continuously Nd-YAG laser welding using a copper foil with a thickness of 600 μm between the two materials, which solves largely the metallurgical incompatibility. The results obtained using a full factorial design, corroborated with metallographic investigations defines the optimal values of the laser beam power, welding speed and laser beam position.

Keywords: laser welding Nd-YAG, process modelling, microstructure, factorial design

1. FUNDAMENTAL BASES

Laser beam welding applied to both homogeneous and heterogeneous joints, is a melting process without using a filler material. Unlike other continuous welding processes, the laser allows a highly accurate punctual contribution of heat. The unification of points ensures a continuous weld. The interaction time is very short, only a few milliseconds for each point [1]. Depending on the material's specific absorption, the welding area will be rapidly heated up to the melting temperature and after cooling the molten bath, a welded seam is obtained. Due to a high energy density (10⁵-10⁶ W/cm²), the heat affected zone is narrow and the penetration is proportional to the power and depends on the position of the focal point. The penetration has a maximum value when the focal point is placed just below the surface of the welded components. The laser beam diameter varies between 0.2 and 133 mm, the lowest values are used for welding.

2. EXPERIMENTAL PROCEDURE

The welding by melting of Ti-6Al-4V and X5CrNi18-10 materials can not be done directly because after the solidification of the molten bath, between Fe and Ti are formed fragile intermetallic phases which can lead to cracking phenomena [2]. Furthermore, there may be an intense oxidation of titanium if the protection of the molten metal bath is deficient. Therefore, Nd-YAG continuously laser welding technique was adopted and for reduction the proportion of unwanted intermetallic phases, a copper foil with a thickness of 600 μm was inserted between the two base materials in order to minimize the metallurgical incompatibilities specific to heterogeneous joints. Through the research conducted, we decided to find a compromise between minimizing the mixing of iron and titanium and ensuring good connections between foil and base metals. To obtain welds with good mechanical resistance, the layer of "isolation" continuity in the molten bath must be maintained. Beam positioning in relation to the joint plane becomes the primary parameter, except the brazing technique where the laser beam is always directed on the filler wire. If the laser beam should be positioned in the plane of the joint, would favour an important mix of the copper foil with both materials, which would lead to a decreased "isolation" function. If the maximum energy will be directed to the interface between the copper foil and one of the base materials, the mixing with the other material will be minimized. The optimal solution involves the shifting of the beam on copper - stainless steel
interface so that the melting and mixing does not lead to intermetallic compounds. Moreover, the energy of interaction between copper and titanium will be minimized and consequently the degree of materials mixing and the formation of intermetallic phases will be reduced.

Using the laser system presented in Figure 1, were conducted three series of tests in end to end configuration:

- the preliminary tests allowed to determine the range of values;
- the power variation from 3000 to 4000 W, maintaining constant the welding speed (increasing the energy intake);
- the speed variation within 2 to 3 m/min, at constant power (reducing energy intake).

For all experiments conducted, the focal spot diameter was 200 μm, and the beam was centered at 40 to 60 μm in relation to the copper – stainless steel interface. The protective gas used was argon.

![Nd-YAG continuously laser welding process](image)

**Fig. 1** Nd-YAG continuously laser welding process

### 3. PROCESS MODELLING

Since the continuous laser welding process is influenced by a large number of parameters, which affect the joint quality, the Minitab software was used for analysis. Among the parameters considered to be important and which will be analyzed during this experiment are the power, the welding speed and the laser beam position (Table 1).

<table>
<thead>
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<th>Parameters</th>
<th>Max</th>
<th>Min</th>
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<tr>
<td>Power, W</td>
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<td>4000</td>
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<tr>
<td>Welding speed, m/min</td>
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<td>3</td>
</tr>
<tr>
<td>Laser beam position, μm</td>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>

A full factorial $2^3$ (level 2, 3 factors) design was set out, with the adjusting factors shown in Table 1, factors that can be controlled during the experiment. They will affect one or more followed responses of the phenomenon under observation.

The response aimed is the quality of the welded joint, given by the ultimate strength. The objective of this experiment is to establish the influence of the controlled factors over the aimed response. Another purpose of these experiments is the optimization that can be done with the help of the same software. Using the input data set, the software automatically generates a design matrix presented in Table 2.
Tab. 2 The design matrix

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</table>

After processing the obtained values were drawn the following graphs for the analyzed response function: the Pareto diagram, the main effects plot, the interaction plot between the influence factors, the contour plot and the surface plot of the response and the optimization plot.

The Pareto diagram is a method of decision and control that allows the use of priorities under different criteria and consists in a graphical representation of various nonconformities. The Pareto analysis is a statistical technique for classification reduced tasks but with significant effect. It is based on the Pareto principle (also known usually as 80/20), which states that 20% of the resources generate 80% of the entire process, or in terms of quality improvement, most problems (80%) have several key causes (20%). Pareto diagram is an ordered histogram of the problems appearing frequency and illustrates how most results are generated by types or categories of cases unidentified [5, 6].

The Pareto diagram effectively solves a problem by identifying and ranking the main causes in order of importance, determines the priority of many practical applications (process improvement efforts) and shows how efforts should be directed [7, 8].

Analyzing the Pareto diagram for the response factor (ultimate strength shown in Figure 2), it can be observed that the main factor of influence is the second order interaction between power and welding speed as the vertical exceeds the 5% threshold.

![Pareto Chart of the Effects](image)

Fig. 2 Pareto Chart of the effects
The influence of the factors is highlighted by the main effects plot in Figure 3. A higher slope of the lines indicates a greater influence and the slope direction indicates that it has a positive or a negative influence. The main effect plot shows that the power and the welding speed affects positively the response factor, while the laser beam position at lower values to higher values, may have a negative influence if the thickness of the weld and alloy titanium interface is not enough to ensure a sufficient connection.

![Main Effects Plot for Ultimate strength](image1)

**Fig. 3** Main effects plot

From the graph shown in Figure 4, it can be evaluate whether between the influence factors exists or not interactions. If the graph lines are parallel or nearly parallel, it can be said that there is no interaction. If the parallelism difference is greater, then are interactions between the factors. Analyzing the interaction plot of the influence factors for ultimate strength it can be observed that there is a significant interaction between power and welding speed, and between power and laser beam position.

![Interaction Plot for Ultimate strength](image2)

**Fig. 4** Interaction plot

Contour plot presented in Figure 5 is used for determining the desired response function of two factors. Since there are three factors of influence, every time one of them will be kept constant while the correlation is made between the other two. Obviously, it can be seen the combination of factors that leads to ultimate strength values between 4000 and 10000 N. The experimental data are represented in 3D (Figure 6) and interpolated to generate a continuous surface of the response function.
During the process characterization was studied which of the control factors influence more the response function (ultimate strength). The optimization of the experiment determines the control factors settings that provide the best response [9]. Phases needed in optimizing multiple responses are:

- design of experiments that will analyze all responses,
- developing a model for each response of the experiment
- setting objectives for each response (minimize, maximize or target) [10].

The optimization method consists in obtaining individual values desired for the response factor (ultimate strength), noted by (D). For this design of experiment, the graphical optimization is shown in Figure 7. It is noted that was find a local optimum which provides an ultimate strength of 11,589 N. The control factors that ensure these values are shown in the upper part of the figure, in square brackets. For the response function was determined the proportion of achievement, which is 99%.
4. CONCLUSIONS

The analysis of continuous laser welding process by a full factorial design led to the following values of parameters that ensure a good quality of welded joints:
- Power 4000 W
- Welding speed, 3 m/min
- The position of the laser beam, 40 μm

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