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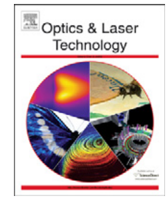


# Statistical modeling of laser welding of DP/TRIP steel sheets

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In this research work, a statistical analysis of the $CO_2$ laser beam welding of dual phase (DP600)/transformation induced plasticity (TRIP700) steel sheets was done using response surface methodology. The analysis considered the effect of laser power (2–2.2 kW), welding speed (40–50 mm/s) and focus position ( $-1$ to 0 mm) on the heat input, the weld bead geometry, uniaxial tensile strength, formability limited dome height and welding operation cost. The experimental design was based on Box–Behnken design using linear and quadratic polynomial equations for predicting the mathematical models. The results indicate that the proposed models predict the responses adequately within the limits of welding parameters being used and the welding speed is the most significant parameter during the welding process.



## 1. Introduction

Tailor welded blanks (TWBs) of advanced high strength steels (AHSS), e.g. DP and TRIP steels, are rapidly gaining popularity in the automotive industry as they allow materials that may be different in thickness or material properties or both to be combined in a single pressed and stamped part in order to improve product performance. They are the result of a never-ending quest for a material that allows increased fuel efficiency while allowing for ease of manufacturability, performance and styling. According to the press release of a material supplier, about 15% of the body structure of a car is made of TWBs parts, which will increase to 25–30% in the next 5–10 years [1].

Welding of AHSS is a challenge since the characteristics of high strength with good formability cannot be sustained under the extensive heating, melting and solidification during welding process. Welding input parameters play a very significant role in determining the quality of a weld joint. The joint quality can be defined in terms of properties such as weld bead geometry, mechanical properties and distortion. Generally, the quality of a weld joint is directly influenced by the welding input parameters during the welding process; therefore, welding can be considered as a multi-input multi-output process. Unfortunately, a common problem that has faced the manufacturer is the control of the process input parameters to obtain a good welded joint with the required bead geometry and weld quality with minimal detrimental residual stresses and distortion [2].

Traditionally, a time-consuming trial and error development effort, with weld input parameters chosen by the skill of the engineer or machine operator should be used to determine the weld input parameters for every new welded product to obtain a welded joint with the required specifications. Then welds are examined to determine whether they meet the specification or not. Finally the weld parameters can be chosen to produce a welded joint that closely meets the joint requirements [3].

Nowadays, application of design of experiment (DoE), evolutionary algorithms and computational network are widely used to develop mathematical relationships between the welding process input parameters and the output variables of the weld joint in order to determine the welding input parameters that lead to the desired weld quality. Koleva [4] studied the influence of electron beam welding parameters, namely electron beam power, welding velocity, distance from the main surface of the magnetic lens to the focus point and the distance between the magnetic lens and the sample surface on the welding depth and width. The experiment was performed with samples of 1H18NT austenitic steel. The author has suggested the use of the developed models for online control of the process. This allows the selection of the optimal levels eliminates the time required for testing and prevents losses of components. The relationship between electron beam welding parameters (beam power, welding velocity and focus position) and weld depth and weld width using response surface methodology (RSM) in order to improve the quality of the process in mass production has been established by Koleva [5]. The author reported that the optimal process parameter values when welding stainless steel are power of 6.5–8 kW, welding

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velocity of 11.667–1.333 mm/s and focus position of 78 mm below the sample surface. Benyounis et al. [6] applied the RSM to investigate the effect of laser beam welding (LBW) parameters (laser power, welding speed and focal point position) based on four responses (heat input, penetration, bead width and width of heat affected zone) in $CO_2$ laser butt welding of medium carbon steel plates of 5 mm thick. The authors found that the heat input plays an imported role in the weld bead parameters and welding speed has a negative effect while laser power has a positive effect on all the responses. Sathavornvichit et al. [7] studied the optimal factors of flux cored arc welding process for steel ST37. The process variables current (250–300 A), voltage (25–30 V), stick out (45–55 mm) and angle (45°–75°) of welding are used in the study of optimization of tensile of weldment by RSM follow a central composite design. The authors indicated that the optimum conditions are 300 A of current, 30 V of voltage, 45 mm of stick out and 60° of angle. The effect of the laser welding parameters on the bead geometry of 2.5 mm thick AISI 304 stainless steel has been evaluated by Manonmani et al. [8]. In this study the relationships between the process parameters (beam power, welding speed and beam incidence angle) and the weld bead parameters (penetration, bead width and area of penetration) have been developed using RSM. To verify the developed models a conformity test run was carried out using intermediate values of the process parameters. It was confirmed that the models developed were accurate since the error percentages were between −4.317% and 3.914%. It was demonstrated that the depth of penetration and penetration area increase as the beam power and the beam angle increase. Also, as the welding speed increases, the width decreases, whereas the penetration depth and area increase to an optimum value and then decrease with further increases in welding speed. This is due to the fact that the effect of key holing is predominant at lower speed and as the welding speed is increased the mode of heat transfer changes from key holing to conduction type of welding. It was reported that the variation in the bead width is slightly affected by the process parameters. Benyounis and Olabi [9] introduced a comprehensive literature review of the application of statistical techniques in the area of welding evaluation and optimization. This review was classified according to the output features of the weld, i.e. bead geometry and mechanical properties of the welds. The authors also gave a comparison between the most common statistical approaches used in the evaluation of welding processes. The authors concluded that the evaluation methods covered in this survey are appropriate for modeling, control and optimizing the different welding process. The survey reveals the high level of interest in the adaptation of RSM and artificial neural networks (ANNs) to predict responses and optimize the welding process. Genetic algorithm (GA) and RSM would reveal good results for finding out the optimal welding conditions. Kishore et al. [10] analyzed the effect of welding process parameters in qualitative manner for welding of AISI1040 steel using processes of shielded metal gas welding. Taguchi method is used to formulate the experimental layout. Exhaustive survey suggest that 5–7 control factors viz., arc voltage, arc current, welding speed, nozzle to work distance and gas pressure predominantly influence weld quality, even plate thickness and backing plate too have their own effect. Design of experiments based on orthogonal array is employed to develop the weldments. The authors showed that the weld speed should be less than 0.45 m/min for 3 mm plate and 0.35 m/min for 5 mm in metal inert gas welding, Taguchi method proved to be robust in design of experiments for evaluation of the quality and the cost of experiments can be reduced by selecting proper orthogonal array. The evaluation of laser welding of DP/TRIP steel sheets are considered one of the essential objectives in transportation industry because there is no sufficient data found in the literature. Padmanaban and Balasubramanian [11] developed an empirical relationship to predict tensile strength of the laser beam welded AZ31B magnesium alloy by incorporating process parameters such as laser power, welding speed and focal position. The experiments were conducted based on a three factor, three level, central composite face centered design matrix with full replications technique. The authors indicated that the welding speed has the greatest influence on tensile strength, followed by laser power and focal position. A maximum tensile strength of 212 MPa is obtained under the welding conditions in which the laser power is 2.5 kW, welding speed of 5.0 m/min and focal position of −1.5 mm. Welding speed is the factor which has the greater influence on tensile strength, followed by laser power and focal position. Ruggiero et al. [12] optimized the weld-bead profile and costs of the $CO_2$ dissimilar laser welding process of low carbon steel and austenitic steel AISI316. The effect of laser power (1.1–1.43 kW), welding speed (25–75 cm/min) and focal point position (−0.8 to −0.2 mm) on the weld-bead geometry (i.e. weld-bead area, upper width, lower width, and middle width) and on the operating cost was investigated using RSM. The authors found that a laser power of 1.1 kW is an optimum input to obtain excellent welded joints produced from austenitic stainless steel AISI316 and low carbon steel. The welding speed is the parameter that most significantly influences the main weld bead dimensions, the middle width and the area, and so it has to be set between 72.6 and 75 cm/min, with the focused position being around −0.44 mm. The welding operating cost achieved with these optimization conditions is cheaper than the expected cost. From literature survey, there are no previous works to show the characterization of laser welding of DP/TRIP steel sheet by statistical approach so it is important to statistically investigate this subject.

However there is no information available in the open literature on the characterization of laser welding of DP/TRIP steel sheet by statistical approach. Hence, this research work aims to develop mathematical models using RSM to predict the heat input and to describe the laser weld bead profile (i.e. weld penetration and welded zone width) for continuous wave $CO_2$ laser butt welding of DP/TRIP steel sheets and to evaluate the variation in their mechanical properties due to the welding process.

## 2. Methodology

A three-factor-three-level Box–Behnken statistical design with full replication was used to optimize and evaluate main effects (linear, quadratic and interaction effects) of the $CO_2$ LBW. Laser beam power, welding speed and focus position are the laser independent input variables of the welding process while the depth of penetration, bead width, tensile strength, limited dome height and welding operation cost are the dependent output variables. The predicting of heat input and welding cost using a DoE approach, is to develop process optimization mathematical models, inside the statistical software Design-Expert which will be carried out in the next work.

In order to find the limitation of the process input parameters, trial simulation runs were carried out by varying one of the process parameters at a time using BEAMSIM software [13]. Statistical software Design-Expert V.8.0.4.1 (Stat-Ease, Minneapolis, MN, USA) was used to code the variables and to establish the design matrix. The independent process variables, the goals of experimental measured responses and design matrix are shown in Tables 1, 2 and 3 respectively.

All the regression model building methods and tools for checking the adequacy of the model are therefore appropriate in the RSM. Assume $y$ to be the observed value of a response variable which depends upon the levels $x_1, x_2, \ldots, x_k$ of some $k$ quantitative factors. The response function is then written as

$$Y = f(x_1, x_2, \ldots, x_k) + \varepsilon \quad (1)$$