Optics and Laser Technology 93 (2017) 149–164

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/jolt

Full length article

Laser dimpling process parameters selection and optimization using surrogate-driven process capability space

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ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form 2 January 2017
Accepted 14 February 2017

Keywords:
Laser dimpling
Zinc coated steel
Surrogate modelling
Design of experiment
Multivariate adaptive regression splines
Process capability space

ABSTRACT

Remote laser welding technology offers opportunities for high production throughput at a competitive cost. However, the remote laser welding process of zinc-coated sheet metal parts in lap joint configuration poses a challenge due to the difference between the melting temperature of the steel (~1500 °C) and the vapourizing temperature of the zinc (~907 °C). In fact, the zinc layer at the faying surface is vapourized and the vapour might be trapped within the melting pool leading to weld defects. Various solutions have been proposed to overcome this problem over the years. Among them, laser dimpling has been adopted by manufacturers because of its flexibility and effectiveness along with its cost advantages. In essence, the dimple works as a spacer between the two sheets in lap joint and allows the zinc vapour escape during welding process, thereby preventing weld defects. However, there is a lack of comprehensive characterization of dimpling process for effective implementation in real manufacturing system taking into consideration inherent changes in variability of process parameters. This paper introduces a methodology to develop *(i)* surrogate model for dimpling process characterization considering multiple–inputs (i.e. key control characteristics) and multiple–outputs (i.e. key performance indicators) system by conducting physical experimentation and using multivariate adaptive regression splines; *(ii)* process capability space (C_p–Space) based on the developed surrogate model that allows the estimation of a desired process fallout rate in the case of violation of process requirements in the presence of stochastic variation; and, *(iii)* selection and optimization of the process parameters based on the process capability space. The proposed methodology provides a unique capability to: *(i)* simulate the effect of process variation as generated by manufacturing process; *(ii)* model quality requirements with multiple and coupled quality requirements; and *(iii)* optimize process parameters under competing quality requirements such as maximizing the dimple height while minimizing the dimple lower surface area.

1. Introduction

Thin zinc coated steel sheets are widely used in the automotive industry due to its high corrosion resistance, especially in body-in-white and closure panels [1,2]. With the advancement of the laser technology, laser welding has been gradually replacing traditional welding methods since it offers cheaper and faster manufacturing process as well as better mechanical and aesthetic joint quality [3–5]. Despite such benefits, it is nonetheless challenging to achieve high quality joint in lap joint configuration of zinc coated steel since the boiling point of zinc (~907 °C) is significantly lower than the melting point of steel (~1500 °C), resulting in highly pressurized zinc vapour on the faying surfaces during the welding process. Left unaddressed, such zinc vapour can easily be trapped inside the molten pool which can lead to welding defects such as porosity, spatter, burn-through, and severe undercuts [6,7].

Over the past few years, significant amount of researches have been conducted to prevent the molten pool from being destroyed by the zinc vapour and several solutions have been proposed which can be classified as:

- *Ventilation* – This method is based on degasification of zinc vapour from the medium without causing any weld defects either by enlarging molten pool [8,9]; stabilizing the keyhole by employing shielding gas [10,11]; creating pre-drilled ventilation channels [12]; applying appropriate spacers at the faying surfaces [13–15]; or adopting a suction method to remove the vapour [16];

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http://dx.doi.org/10.1016/j.optlastec.2017.02.012
0030-3992/

Nomenclature

D_H	dimple height
D_U	dimple upper surface area
D_L	dimple lower surface area
S_s	scanning speed
α	incidence angle
F_O	focal offset
L_T	laser track
KCCs	key control characteristics
KPIs	key performance indicators
N_i	number of KCCs
N_j	number of KPIs
N_k	number of experimental configurations
N_l	number of experiment replications
d	number of dependent KPIs
$N_s^{(k)}$	number of KPIs in the k^{th} experimental configuration
$KCC_i^{(k)}$	i^{th} KCC value in the k^{th} experimental configuration
$KPI_j^{(k,l)}$	j^{th} KPI value in the k^{th} experimental configuration at the l^{th} replication
$\mu_{KPI_j^{(k)}}$	mean value of the j^{th} KPI in the k^{th} experimental configuration
$\sigma_{KPI_j^{(k)}}$	standard deviation of the j^{th} KPI in the k^{th} experimental configuration
$\hat{\mu}_{KPI_j}$	estimated mean value of the j^{th} KPI
$\xi_{KPI_j^{(k)}}$	success rate of the j^{th} KPI in the k^{th} experimental configuration
$\xi_{KPI_1^{(k)} \cdots KPI_d^{(k)}}$	success rate of the dependent KPIs in the k^{th} experimental configuration
$\hat{\xi}_{KPI_j}$	estimated success rate of the j^{th} KPI
$\hat{\xi}_{KPI_1 \cdots KPI_d}$	estimated success rate of dependent KPIs
$F_{\mu_{KPI_j}}$	deterministic surrogate model of the j^{th} KPI
$F_{\xi_{KPI_j}}$	stochastic surrogate model of the j^{th} KPI
$F_{\xi_{KPI_1 \cdots KPI_d}}$	stochastic surrogate model of dependent KPIs
PDF	probability density function
SR	success rate
β	minimal desirable success rate
LL	lower limit
UL	upper limit
KCC – space	process parameter space
$\mathbf{C_p}$ **– space**	process capability space
$\mathbf{DC_{p_j}}$ **– Space**	deterministic process capability space of j^{th} KPI
$\mathbf{SC_{p_j}}$ **– Space**	stochastic process capability space of j^{th} KPI
$\mathbf{DC_p}$ **– Space**	deterministic process capability space
$\mathbf{SC_p}$ **– Space**	stochastic process capability space

- *Inserting a thin metal foil* – This involves adding another material (e.g. Al & Cu) into the faying surface which absorbs zinc vapour or reacts with zinc vapour in such a way that a liquid alloy with a high boiling point is formed [17,18];
- *Tandem beams* – This approach employs a dual laser beam or a secondary heat source. The first beam applies pre-heating which vapourizes zinc coating and second beam performs actual welding [19–21];
- *Controlling keyhole oscillation* – The molten pool shape can be controlled based on the pulsed wave mode of laser beam so that more stable keyhole oscillation can be achieved, allowing the zinc vapour to escape during the keyhole closure [22,23]
- *Surf-sculpt* – This method creates surface features from the base metal by repeated movement of the low power on-focus laser beam in a short distance. These features increase surface area of the material and can be utilized as a spacer between the faying surface in lap joint [24,25].

All of the above solutions have been shown to produce satisfactory welds in lap joint configuration. However, they do have number of disadvantages due to: (*i*) challenges in development of system automation for robotic joining process (see *inserting a thin metal foil* solution); (*ii*) increased system complexity (see *ventilation* and *tandem beam* solutions) due to the need for installation of additional equipment which increases processing cost as well; and, (*iii*) increased cycle time (see *tandem beam*, *controlling keyhole oscillation* and *surf-sculpt* solutions) due to lower processing speed.

A promising technique for mitigation of zinc vapour is "*laser dimpling*" which makes a dimple on the faying surface of the upper sheet metal by rapid and single movement of the laser beam. Hence, the zinc vapour is vented out through the generated gap between the faying surfaces which is illustrated in Fig. 1. The laser dimpling process has been used by the automotive industry as it does not require any additional equipment and can be performed using the same laser source and fixture adopted for welding [26,27]. Furthermore, it is not restricted by the shape and curvature of the workpiece and weld location.

The physical principle behind laser dimpling process can be explained by the "*humping effect*" which is influenced by the heat and mass transfer in the molten pool. In general, humps occur periodically along the weld bead which deteriorate the homogeneity of molten pool. In laser welding process, when the beam hits the workpiece, it creates a deep narrow cavity, known as keyhole. While laser beam is moving, the liquid material at the bottom of the keyhole flows upwards to the rear of the molten pool and generates a backward trail of a thin jet due to the surface tension on the keyhole walls. The solidification of this jet on the surface forms the hump at the rear and leading to a valley of cavity at the front which is given in Fig. 2. There has been significant research which look at the humping effect as a negative phenomenon during joining process, explained causes of humping effect and described ways to suppress the occurrence of the hump [28–32]. However, the "*humping effect*" can be beneficially utilized by laser dimpling process to create the required gap in lap welding of zinc coated steels.

According to Gu [26,27], humping effect was used to generate dimple for laser welding process first, by studying the influence of a single parameter, focal offset, on the dimple height. Then, they used this information to generate dimples at different scanning speed and incidence angle, while other parameters such as focal offset were kept constant. Results indicated that dimple height monotonically decreased with increasing both scanning speed and incidence angle; whereas, the dimple height firstly, increased and then decreased whilst increasing the focal offset. In a more recent study conducted by Colombo and Previtali [33] applied univariate linear regression model to determine influence of scanning speed on the dimple height keeping constant laser power, focal offset, and laser track. They found that linear energy, which is the amount of the energy supplied per unit time, was the primary factor affecting the dimple height. However, this study has limitation as authors considered only the influence of a single process parameter without exploring other important process parameters and their interactions.

The existing literature has focussed mainly on single–input (i.e. scanning speed) and single–output (i.e. dimple height) scenario which is necessary but not sufficient to give a complete characterisation of the dimpling process. Furthermore, the laser material processes are characterized as multiple–inputs and