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ASSESSMENT OF THE EFFECT OF ND:YAG LASER PULSE OPERATING PARAMETERS ON THE METALLURGICAL CHARACTERISTICS OF DIFFERENT TOOL STEELS USING DOE SOFTWARE

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To ensure the reliability of repair welded tool surfaces, clad quality should be improved. The relationships between metallurgical characteristics of cladding and laser input welding parameters were studied using the design of experiments software. The influence of laser power, welding speed, focal point position and diameter of welding wire on the weld-bead geometry (i.e. penetration, cladding zone width and heat-affected-zone width), microstructural homogeneity, dilution and bond strength was investigated on commonly used tool steels 1,2083, 1,2312 and 1,2343, using DOE software.

Key words: laser cladding, tool steel, DOE software

Procjena utjecaja operativnih parametara Nd:YAG pulsnog lasera na metalurška svojstva različitih alatnih čelika pomoću DOE softvera. Poboljšanje kvalitete navarenog sloja nužno je za osiguranje pouzdanosti površina alata, obrađenih postupkom reparaturnog navarivanja. Odnos između metalurških osobina navarenog sloja i ulaznih parametara laserskog zavarivanja istražen je pomoću softvera Design of experiments. Utjecaj snage lasera, brzine zavarivanja, položaja žarišta i promjera žice za zavarivanje na geometriju navara (t.j. na penetraciju, širinu navara i širinu zone utjecaja topline), mikrostrukturna homogenost, miješanje i snaga spoja istraženi su na uobičajenim alatnim čelicima 1,2083, 1,2312 i 1,2343 pomoću softvera DOE.

Ključne riječi: reparaturno navarivanje, alatni čelik, DOE programska oprema

INTRODUCTION

Polymer injection molds often require some form of repair cladding during the operation and whole life cycle due to the different mechanisms of failure in the molds [1-3]. Special processes and welding procedures are required for repair cladding due to the considerable metallurgical concerns and low weldability of tool steels. Among other known processes, laser cladding is becoming an increasingly attractive technique due to the properties of laser radiation: high input energy, low distortion, minimum dilatation between the base material and clad, as well as a more refined microstructure due to high cooling rates [4]. Despite the fact that the necessary equipment and filler materials are readily available on the market, there is a lack of published scientific work on pulse laser repair cladding of tool steels. The input parameters of laser welding determine the shape of laser clad-bead and the metallurgical properties of clad [5]. The primary objective of this work is to establish and statistically analyze the optimal conditions of pulsed laser input parameters for cladding of tool steels using preplaced wires.

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EXPERIMENTAL PROCEDURE

Material

The steels used in the present study are commercially available tool steel types 1,2083 (X42Cr13Mo4), 1,2343 (X38CrMoV51) and 1,2311 (X40CrMnMo7), which are commonly used for dies for die casting and plastic injection molding. Test plates from steels 1,2083 and 1,2343 were vacuum-quenched and tempered to level of hardness 54 HRC and 47 HRC, while the plate made of steel 1,2311 was used in a pre-hardened state (33 HRC). The filler wires used in the experiments are commercially available wires usually used for MIG welding, having similar nominal chemical composition to the base material. In order to investigate the influence of wire diameters on the clad shape, we used two different wire diameters of 0,35 and 0,5 mm.

Laser cladding

The cladding of test specimens was performed with a pulsed Nd:YAG laser (LASAG model SLS200 CL60) by melting of the preplaced filler wire. Argon gas 5,0 with flow rate of 5 l/min was used for shielding. The la-

Table 1. **Mean values of control factors at each level**

Factor	P	Mean	
		Level 1	Level 2
A	P_p / kW	1,5	2
B	τ / ms	8	12
C	υ / Hz	5	10
D	v / mm/s	1	1,25
E	Φ / mm	0,33	0,5
F	material	1,2343	1,2312

ser beam was moved in automatic mode; only the wire was preplaced by a operator. The influence of operator's skills on the results of manual laser cladding is minimal, so it can be neglected [6]. The focal distance of lenses was 160 mm and was controlled by precise laser triangulation. Preliminary trials using different values of laser peak power (P_p), laser feed rate (v), pulse frequency and pulse duration (τ) were undertaken to determine feasible test conditions (Table 1).

Design of experiment

Laser cladding tests were performed to determine the laser operating parameters having the greatest influence on the clad geometry and dilution ratio, and to examine the correlation between the operating parameters and the metallurgical properties of the clad. The analysis of experimental results was based on the analysis of variance (ANOVA) method. A 2^3 design was executed. The experiment was carried out according to the designed matrix in a random order to avoid any systematic error (Table 2). The transversally sectioned specimens of clad were measured using an optical microscope and adequate software. The average of three weld profiles was recorded for each response. Responses φ_a, φ_e, DR and fraction P/R were calculated according to the equations shown in Figure 1. A test of significance of the regression models, a test of significance of individual model coefficients and the lack-of-fit test were also performed. Step-wise regression method was used to automatically eliminate the insignificant terms of the model. The resulting ANOVA (Table 3) summarizes the analysis of variance for each response and shows the significant terms of model.

Geometrical and microstructural analysis

After laser cladding, the specimens were sectioned transversally to the clad track, polished with SiC paper and diamond paste. The samples were than etched with Nital 2 % etchant. The geometry and microstructure of the clad track were than studied by optical microscopy and analyzed with PRIMO software.

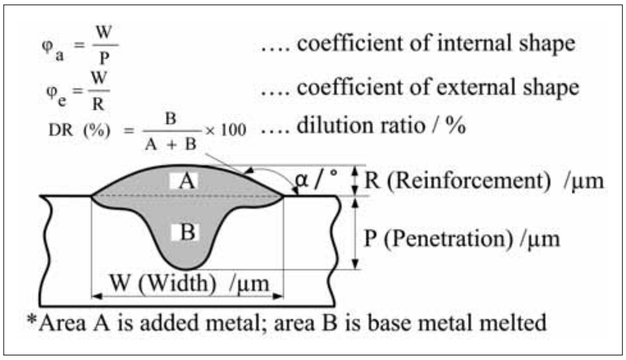

Figure 1 Principal clad geometry in cross section and response values

RESULTS AND DISSCUSION

The analysis of variance determines the relative influence of each factor. The analysis of variance (ANOVA) on the measured data suggests the following findings.

Reinforcement

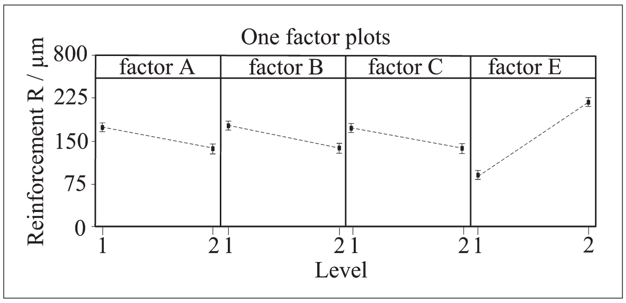

Figure 2 Plot of main effects on the reinforcement response

On the basis of ANOVA results, we can conclude that P_p, τ, Φ and υ are significal model terms associated with reinforcement. In the Figure 2 it is clear to observe, that:

– lower reinforcement is attained with higher values of P_p, τ and υ. We therefore get higher melting loss at higher values of laser caldding parameters;
– larger wire diameter on both materials gives clad with higher reinforcement.

Penetration

On the basis of interaction plot (Figure 3) we can conclude that the penetration ratio is similar for smaller diameters of the filler wires. For larger wire diameters we can observe greater penetration in the material 1,2343. The lower thermal diffusivity of 1,2343 explains the higher penetration of clad in the base material compared to 1,2312.

According to the performed tests, we can conclude that the most significant laser processing parameters of pulse cladding are duration of pulse and peak power. The wire diameter is a less significant parameter. In order to investigate further, we designed a more detailed experiment on three different types of tool steels:

Table 2 **Design matrix with process factors and experimentally measured responses**

Std. O.	Factors						Responses							
	A	B	C	D	E	F	W/ μm	P/ μm	R/ μm	α/ °	DR/ %	φ_e	φ_a	P/R
1	1	1	1	1	1	1	827	430	160	152	30,22	5,1	1,92	2,69
2	2	1	1	1	1	2	1 210	845	96	164	17,59	12,6	1,43	8,8
3	1	2	1	1	1	2	1 242	623	86	168	18,46	14,4	1,99	7,24
4	2	2	1	1	1	1	1 025	944	114	161	13,33	8,9	1,09	8,28
5	1	1	2	1	1	2	1 054	532	112	161	22,07	9,41	1,98	4,75
6	2	1	2	1	1	1	814	701	62	165	8,16	13,1	1,16	11,31
7	1	2	2	1	1	1	1 101	498	60	167	14,37	18,3	2,21	8,3
8	2	2	2	1	1	2	1 411	947	44	172	5,48	32,0	1,49	21,52
9	1	1	1	2	1	2	1 062	425	122	156	36,32	8,07	2,5	3,48
10	2	1	1	2	1	1	1 033	842	101	157	12,44	10,2	1,23	8,34
11	1	2	1	2	1	1	947	602	120	160	16,16	7,89	1,57	5,02
12	2	2	1	2	1	1	1 291	944	65	169	10,91	19,8	1,37	14,52
13	1	1	2	2	1	1	837	821	104	148	13,19	8,05	1,02	7,89
14	2	1	2	2	1	2	1 239	827	83	171	11,52	14,93	1,5	9,96
15	1	2	2	2	1	2	1 195	558	83	165	19,2	14,4	2,14	6,72
16	2	2	2	2	1	1	821	832	52	165	6,23	15,79	0,99	16
17	1	1	1	1	2	2	1 010	399	264	138	53,95	3,83	2,53	1,51
18	2	1	1	1	2	1	99	577	242	132	42,65	4,13	1,73	2,38
19	1	2	1	1	2	1	1 007	334	256	147	51,46	3,39	3,01	1,3
20	2	2	1	1	2	2	1 388	861	180	158	25,93	7,71	1,61	4,78
21	1	1	2	1	2	1	968	250	245	142	61,96	3,95	3,87	1,02
22	2	1	2	1	2	2	1 192	675	200	145	31,74	5,96	1,77	3,38
23	1	2	2	1	2	2	1 195	529	185	144	37,19	6,46	2,26	2,86
24	2	2	2	1	2	1	1 171	639	136	164	19,09	19,09	1,83	4,7
25	1	1	1	2	2	1	835	200	297	127	75,45	2,81	4,18	0,67
26	2	1	1	2	2	2	1 202	767	203	156	32,67	5,92	1,57	3,78
27	1	2	1	2	2	2	1 263	545	211	151	40,57	5,99	2,32	2,58
28	2	2	1	2	2	1	1 046	707	224	139	28,8	4,67	1,48	3,16
29	1	1	2	2	2	2	1 043	355	250	141	53,08	4,17	2,94	1,42
30	2	1	2	2	2	1	994	446	234	139	48,51	4,25	2,23	1,95
31	1	2	2	2	2	1	1 023	347	219	143	48,12	4,67	2,95	1,58
32	1	2	2	2	2	2	1 427	814	143	162	22,42	9,98	1,75	5,69

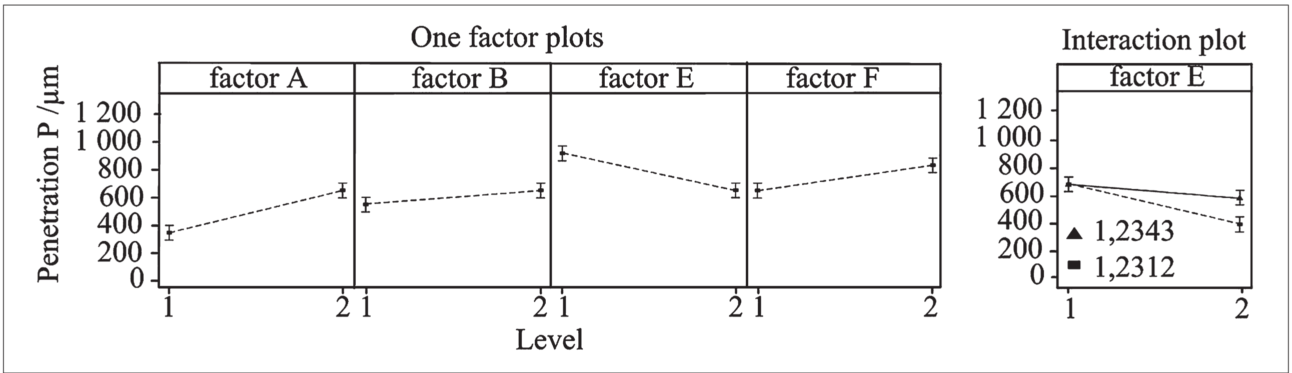

Figure 3 Main effect plots and interaction plot on process response penetration in μm

1,2083, 1,2343 and 1,2312 (Figure 4). Therefore, a three level and three factor DoE has been considered. In this way, ANOVA results with a quadratic model. This shows the best fit to the experimental data. The resulting response surface for the adjusted model is shown in Figure 5, where the values of fraction P/R vary. Other pa-

Table 3 **ANOVA partial sum of squares for reinforcement**

Source	Sum of squares	d.f	Mean square	F
Model	1,59 x10^5	4	39 772,66	93,3
P_p	11 063.28	1	11 063,28	26,8
τ	11 137.81	1	11 137,78	26,9
υ	8 745,03	1	8 745,03	21,1
Φ	1,281 x10^5	1	1,28x10^5	310
Residual	11 140,84	27	412,62	
Cor total	1,702x10^5	61		
Note: R^2=0,9346; predicted R^2=0,9081; adjusted R^2=0,9249; adequate precision= 29,185				

rameters remain at fixed values: υ=10 Hz; v=1,25 mm/s and Φ=0,5 mm).

On contour graphs we can identify three zones as a function of P/R fraction. These three zones are in correlation with the clad bond strength. More importantly, no defects such as cracks, pores and incomplete fusion were present in the II. zone (2 < P/R < 3).

Weld metal microstructural characteristics

Presence of defects due to incomplete fusion on the fusion line was noticed in some deposits (zone I). Cracks and micro cracks in the clad layer are one of the major concerns in laser pulse cladding, as they can affect the clad application. Cracks were found at high pulse energy (Figure 6a).

The cracks starts to emerge at a value of fraction P/R higher than 3,5 (zone III).

Macro-cavities are also generated during pulsed laser cladding. These cavities are initiated at the root of clad during laser cladding in deep penetration mode (P/R>4). They are located mostly at the edges and at the root of the bead (Figure 6b).

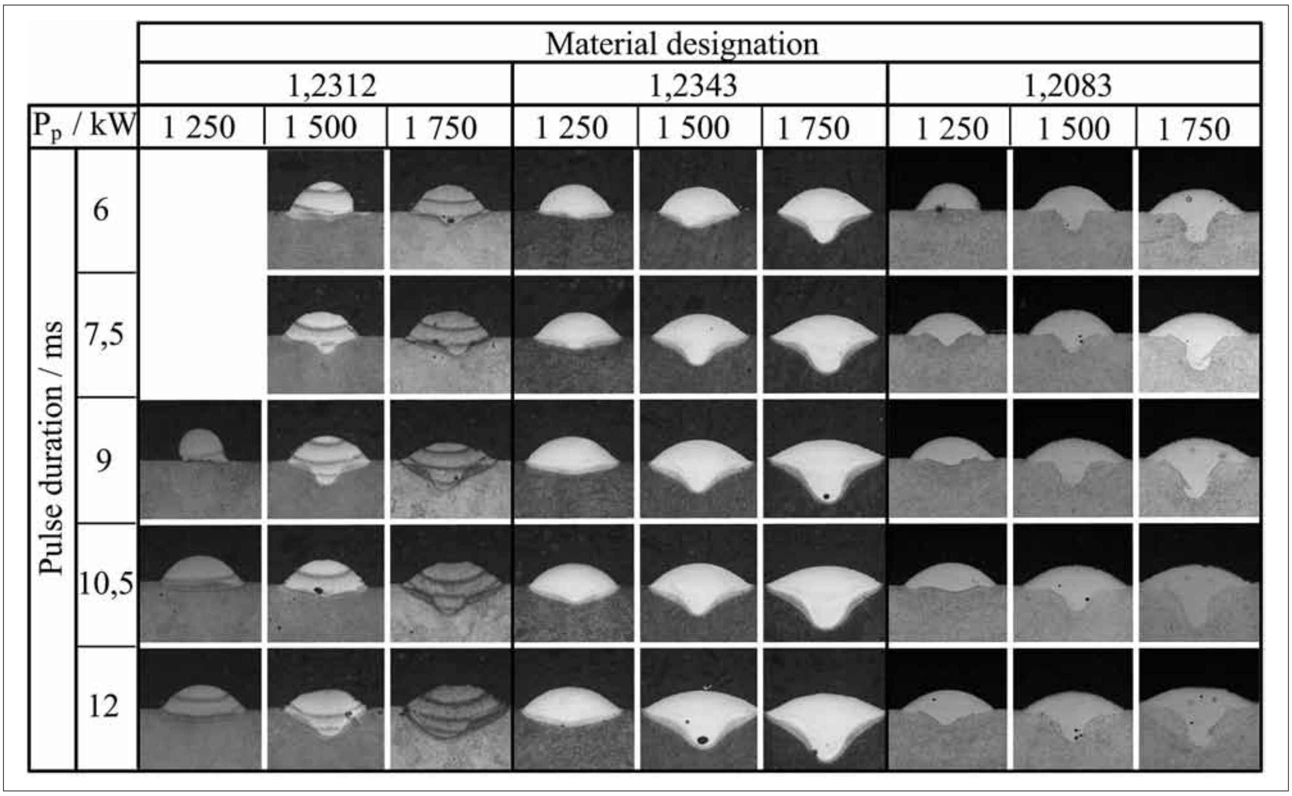

Figure 4 Clad shapes in the cross section

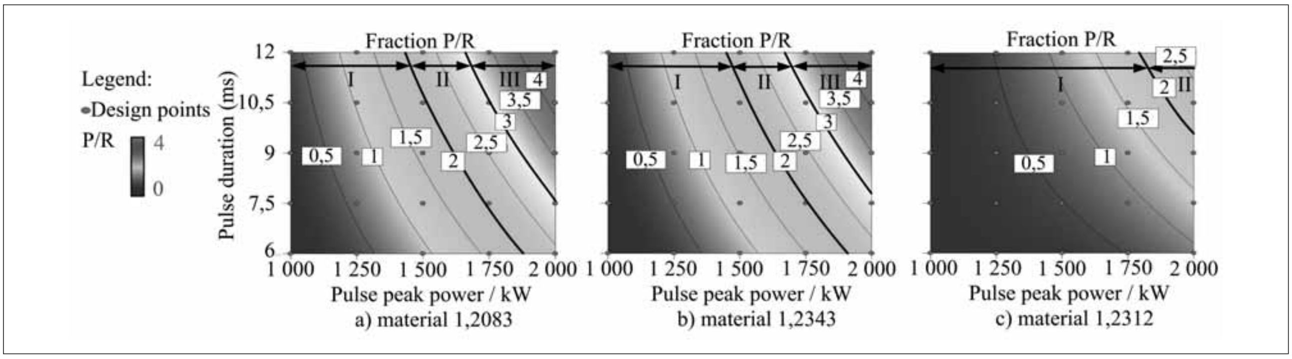

Figure 5 Contour graph shows the effect of P_p and τ on the fraction P/R for different types of steels

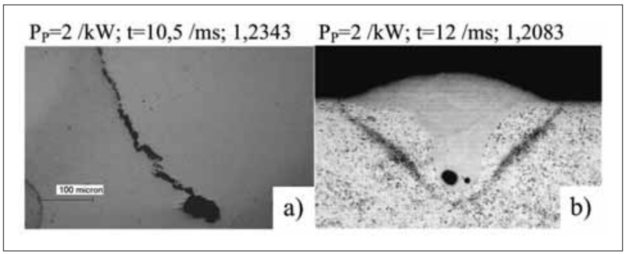

Figure 6 a) clad solidification crack
b) porosity in clad root

CONCLUSIONS

The main findings of the presented research, within the factor limits, can be summarized as follows:

- input laser parameters related to pulse energy affect the clad shape. Clad height is reduced with increasing pulse energy;
- the depth of penetration into the substrate increases with increasing pulse energy, pulse duration and pulse frequency, but decreases with increasing wire diameter;
- penetration depth is also strongly affected by the type of material. Steel with lower thermal conductivity (1,2083) shows a higher penetration rate;
- laser input parameters should be chosen according to the physical properties of material, especially thermal conductivity;
- higher values of fraction P/R bring an increased occurrence of porosity and cracking of clad. This can be eliminated by slowing the cooling rate, by reducing the cladding speed or by conventional preheating.

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