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LASER REPAIR WELDING OF MOLDS WITH VARIOUS PULSE SHAPES

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Repair welding of cold-work tool steels with conventional methods is very difficult due to cracking during remelting or cladding and is generally performed with preheating. As an alternative, repair welding with laser technology has recently been used. This paper presents the influence of different pulse shapes on welding of such tools with the pulsed Nd:YAG laser. Repair welding tests were carried out on AISI D2 tool steel, quenched and tempered to hardness of 56 HRc, followed by microstructural analysis and investigation of defects with scanning electron microscopy. Test results suggest that it is possible to obtain sound welds without preheating, with the right selection of welding parameters and appropriate pulse shape.

Key words: laser, repair welding, pulse-shaping, cold-work tool steel

Lasersko reparaturno zavarivanje alata s različitim oblicima impulsa. Reparaturno zavarivanje alatnih čelika za rad na hladno konvencionalnim metodama je vrlo teško zbog pukotina nastalih tokom pretaljivanja i navarivanja i općenito vrši se uz predgrijavanje. U posljednje vrijeme se kao alternativna metoda koristi reparaturno zavarivanje upotrebom laserske tehnologije. Ovaj rad predstavlja utjecaj različitih oblika impulsa na zavarivanje alatnih čelika s pulsnim laserom Nd:YAG. Reparaturno zavarivanje testirano je na alatnom čeliku AISI D2, termički obrađenim na tvrdoću 56 HRc, poslije čega je provedena analiza mikrostrukture i traženje defekata skeniranjem elektronskim mikroskopom. Rezultati testiranja sugeriraju da je moguće izvesti dobre zavare bez predgrijavanja pravilnim izborom parametara zavarivanja i odgovarajućeg oblika impulsa.

Ključne riječi: laser, reparaturno zavarivanje, oblikovanje impulsa, alatni čelik za rad na hladno

INTRODUCTION

Repair welding of damaged and worn-out tools is a measure which can increase productivity and lower production costs to a great extent. Such example of tools are also injection moulds that frequently require repairs, including welding, due to errors during manufacture, changes in the design of the tool part and/or incidence of failures during the service life.

The majority of tool steels is commonly considered as non-weldable, because of their high carbon and high alloy elements content [1]. Repair welding of tools is generally performed with gas tungsten arc welding (GTAW). Such repair of the tool is carried out with preheating and post-weld heat treatment, to avoid solidification cracking and residual stresses induced by transformations during welding [2, 3]. The most critical is the heat affected zone (HAZ), which can be very hard and brittle and susceptible to cracking if the tools are not heat treated properly. However, many items are successfully repaired in the hardened and tempered condition [4]. When this can be done safely, it avoids the need for annealing before the repair, hardening and tempering afterwards, and the possible costly correction of dimensional changes caused by heat treatment.

For such sensitive tools, the laser technology has recently been used, where localized heating effect reduces distortions during welding and allows the repair without any heat treatment. The other benefits of laser welding are also narrow HAZ, negligible undercuts, the precise positioning and control of the spot of incidence and its movement. This is especially important by repairing narrow or sharp areas and areas close to high polished surfaces, where conventional welding would cause undesired results regarding the amount of mechanical treatment and possible deformations.

Pulsed laser repair welding is receiving a great attention in the academic and industrial research. Evolution of microstructures in tools after welding was demonstrated in research work by Vedani, who compared microstructures in claddings on several tool steels, processed with laser and GTAW [4]. Some other authors demonstrated suitability of laser beam welding process for refurbishment and cladding in the field of tooling [5, 6]. Several authors also published some papers related to optimization of pulsed laser welding processes, especially regarding pulse shapes and their effect on micro-

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structure growth, thermal field distribution and defect prevention for a large variety of materials [7-10].

According to a literature survey, there still remains a lack of research in microstructural behavior of several groups of tool steels after repair welding. One of them is high-carbon, high-chromium cold-work tool steel. Tool steels of this type are air hardening and attain full hardness when cooled in still air [11]. These steels have high resistance to softening at elevated temperatures and exhibit excellent resistance to wear. Typical applications of these materials include deep drawing, blanking, forming and thread rolling dies; shear and granulator blades and high wear resistant and intricate moulds for plastic injection.

These steels contain a massive amount of carbides, which make it very difficult to weld. It is preferable to weld them in the annealed condition whenever feasible. In order to avoid cracking, these tools and dies should never be welded without preheating, regardless of the heat-treatment condition (annealed or hardened). Regarding conventional repair welding, the preheating and interpass temperature for these materials should be between 370 – 480 °C. This shows that welding of these steels in cold is very risky and by conventional processes almost impossible.

The present paper presents an experimental investigation of various pulse shapes affecting solidification and microstructure behavior and defect formation of a cold work tool steel after surface remelting and cladding with wire by a pulsed Nd:YAG laser.

EXPERIMENTAL PROCEDURE

The material, investigated in this research is an EN X160CrMo12-1 (AISI D2) tool steel. Simulation of welding was performed on samples (10×15×100 mm bars) that were hardened and tempered to achieve hardness of 56 HRc. Laser remelting and overlay welding was performed using pulsed 200 W laser equipment (Lasag Easy welder SLS CL 60) and a Castolin filler wire with 0.4 mm diameter. Chemical compositions of parent and filler material are presented in Table 1. The explanation of the influence of laser beam pulse shape on the repair welding is demonstrated with three laser pulse shapes (Figure 1).

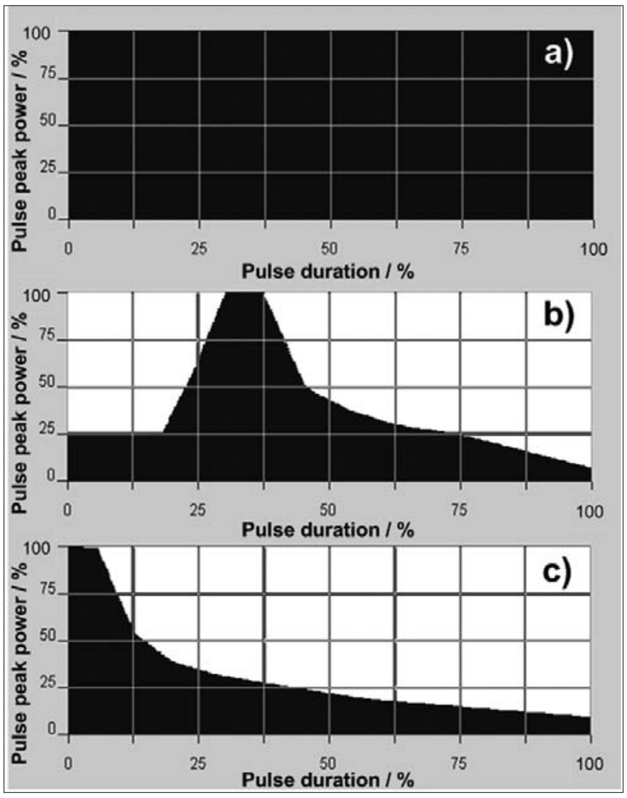

Figure 1. Investigated laser pulse shapes; a) pulse shape A, b) pulse shape B, c) pulse shape C

Type A laser pulse shape is a classical rectangular pulse shape with the constant power distribution during its duration time, which varies in the case of shapes B and C. Laser parameters for the investigated pulse shapes are presented in Table 2.

To catalogue the effect of various pulse shapes on solidification behavior, single spot remelting and continuous multi-seam claddings were performed. After that the metallographic analysis was carried out. Samples for the metallographic analysis were cut with precision cutter, polished and etched with Vilella solution. Examination of prepared samples was later carried out by scanning electron microscopy (SEM).

Table 1. **Chemical composition of base and filler material (OES analysis).**

Material	Chemical composition / wt.%								
	C	Si	Mn	Cr	Mo	Ni	V	W	Fe
X160CrMoV121	1,53	0,35	0,40	12	1,0	-	0,85	-	bal.
filler wire	0,73	1,8	0,22	9,2	0,26	0,1	0,28	0,1	bal.

Table 2. **Laser parameters for the investigated pulse shapes.**

Pulse shape	Laser parameter			
	Focal length /mm	Pulse peak power / kW	Pulse duration / ms	Pulse energy / J
A	160	1,0	10	10
B	160	1,45	18	10
C	160	1,2	60	22,7

RESULTS AND DISCUSION

The analysis of spot apices made with single pulse remelting reveals the major problem in welding of cold-work tool steels i.e. shrinkage cracking, as a consequence of rapid solidification. Rectangular laser pulse (type A) is commonly used pulse for welding of mild steels, stainless steels and low alloyed tool steels. From the Figure 2a, it can be inferred that this type of pulse is inappropriate for welding of the investigated material, due to major cracking in the spot. The cracks originate from the centre and propagate towards the periphery of the remelted spot in the length of 200 μm.

Fewer issues arise from remelting with the type B pulse shape, shown in Figure 2b. There is still some noticeable cracking with the crack length of approx. 100 µm. Influence of type C pulse shape and process parameters on solidification behavior of molten spot is depicted in Figure 1c. The long ramped-down pulse is superior to pulses A and B. In this case no deficiencies on the apex of remelted spot can be perceived. This type of pulse shape and parameters are beneficial because of its relatively long lasting annealing effect. Essential is the last 90 % of the pulse, i.e. 50 ms, that make solidification process run slower and the stresses not exceeding the tensile strength of material with the newly formed structure. The distinctive round area in the center of the spot is also characteristic for this type of laser pulse. This is due to a different microstructure in this area, which is the consequence of specific pulse action.

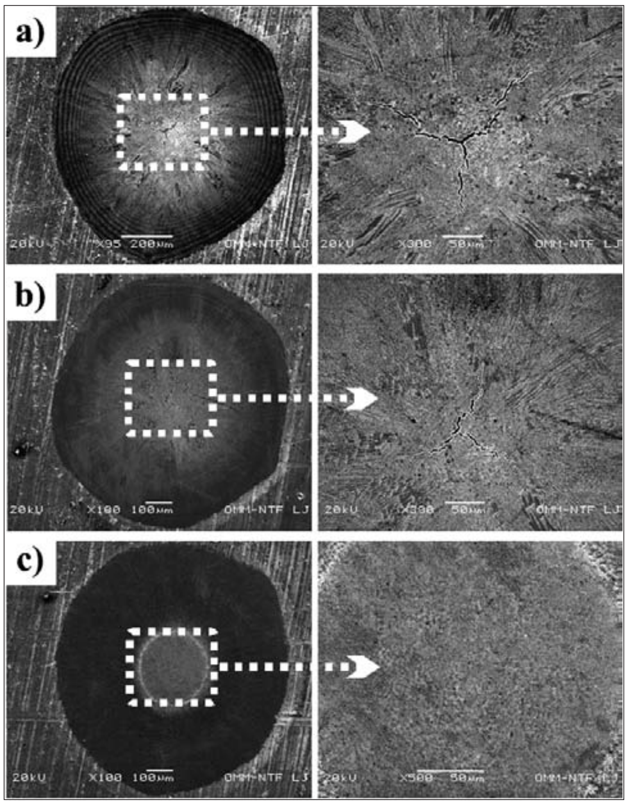

Figure 2. Apices of spots remelted with single pulse; a) type A pulse, b) type B pulse, c) type C pulse.

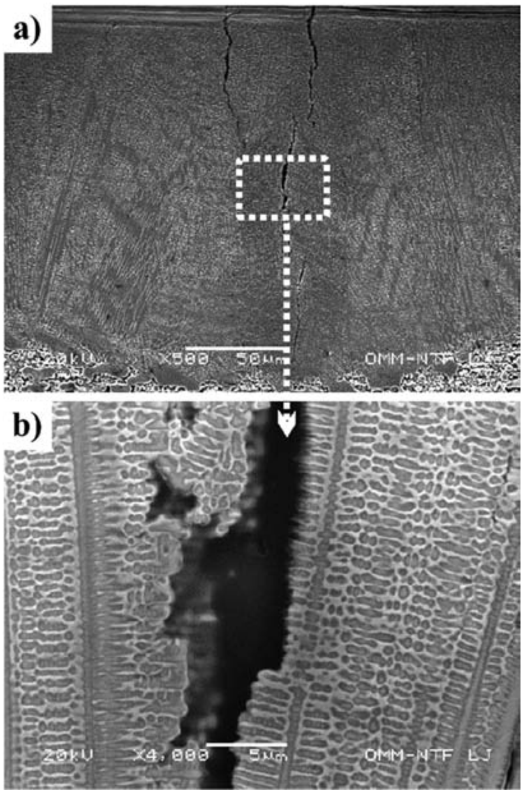

Figure 3. Cross section of the spot, remelted with type A laser pulse; a) macro section, b) higher magnification image of microstructure by the crack.

Microstructures formed in the molten pool under type A and B conditions are basically the same. As shown in Figures 3a and 3b, the microstructure consists of fine columnar dendrites with very narrow dendrite arm spacing. The dendrites are perpendicular to the fusion line and grow towards the spot surface center. Columnar dendrite solidification occurs in a case of low temperature gradient and when the most under-cooled area of the melt is distant from the solidification line. This kind of solidification depends on under-cooling range, which is significantly larger than the grain diameter. Large distance of the solidus-liquidus region enables lower actual temperature compared to the effective temperature of the melt [12]. Laser, due to localized high energy input, causes rapid melting and also very quick solidification. This causes great distance between the S-L phase, but the time for growth is very short, therefore only primary dendrite arms can develop. Because of fast solidification, cracking occurs as a consequence of high tensile stresses, due to solidification contraction. Consequently cracks form as a tearing between dendrites in the central region of the spot. The cracks are not uniform, they occur in a great number, and extend from the apex to the root of remelted spot.

Figures 4a and 4b show the macro section and the detailed image of characteristic microstructure performed under pulse C shape and parameters. The majority of microstructure is basically similar to the one mentioned above, with the exception of central surface area and a few very elongated columnar dendrites, extending from

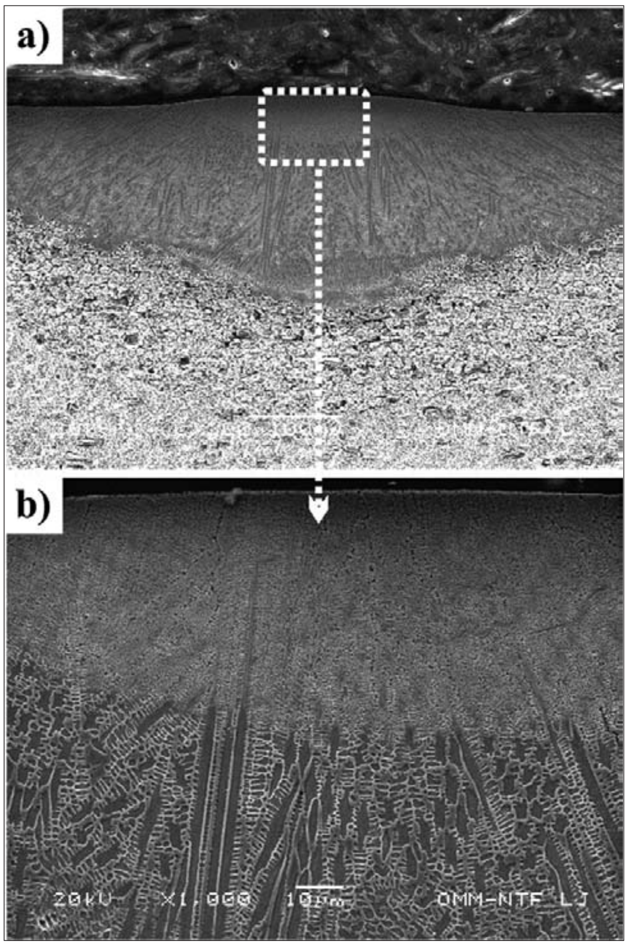

Figure 4. Cross section of the spot, remelted with type C laser pulse; a) macro section, b) detailed picture of distinctive microstructures

the fusion line on the root side of the bead, through complete remelted region, to the apex. As mentioned above, the distinctive circle inside the spot surface originates in a specific microstructure, which is different from that in the remaining molten volume. As depicted in Figure 4b, this surface area consists of microstructure, based on columnar dendrites, but the long pulse duration time ensures more time for solidification and formation of secondary dendrite arms. This results in a fine dendritic microstructure with very narrow dendrite arm spacing (less than 1 μm).

The effect of pulse shaping and chosen process parameters on defect formation is explicitly expressed by laser cladding with wire. In the case of processing with pulse A, cracking occurs in a far greater extent. The cracks propagate through the whole overlay into the base material.

When cladding with type B pulse, the cracking also appears but the cracks are shallower compared to those performed under pulse A and their appearance is not uniform across the seam but they randomly occur in the length of 0,1–0,3 mm. In the case of welding with pulse shape C, no cracking occurs. The results suggest that this type of pulse shape is superior to other compared shapes and that it ensures defect free remelting and cladding.

CONCLUSIONS

The main objective of this research was to find the suitable laser pulse shape for welding of cold-work tool steels. The following conclusions can be summarized:

The analysis of spot apices made with single pulse remelting reveals that the only suitable pulse shape is the C shape. Only in this case, no cracking occurs, while during processing with pulses A and B shrinkage cracks appear in the center of remelted spots.

The microstructure analysis shows that the microstructure is basically the same, independent of the pulse shape. Mostly the columnar dendritic microstructure occurs, with the exception of central surface area of the spot melted with type C pulse. This distinctive semicircle under the surface originates in a specific, fine dendritic microstructure.

The effect of pulse shaping and chosen process parameters on defect formation is explicitly expressed by laser cladding with wire. Sound welds in cold (without preheating of the base material) can be obtained by the pulse with the annealing effect of relatively long duration (over 40 ms), i.e. type C pulse only.

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Note: The responsible translator for English language is Manuela Bojnec.