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PROBLEMS IN REPAIR-WELDING OF DUPLEX-TREATED TOOL STEELS

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The present paper addresses problems in laser welding of die-cast tools used for aluminum pressure die-castings and plastic moulds. To extend life cycle of tools various surface improvements are used. These surface improvements significantly reduce weldability of the material. This paper presents development of defects in repair welding of duplex-treated tool steel. The procedure is aimed at reduction of defects by the newly developed repair laser welding techniques. Effects of different repair welding process parameters and techniques are considered. A microstructural analysis is conducted to detect defect formation and reveal the best laser welding method for duplex-treated tools.

Key words: repair welding, nitrided tool steel, PVD coating, die casting

Problemi kod reparaturnog zavarivanja alatnog čelika sa duplex zaštitom. U radu su istraženi problemi kod laserskog zavarivanja alata za lijevanje u industriji tlačnog lijeva aluminija ili plastike. Za produženje života alata primjenjena su različita poboljšanja površine. Ovakva poboljšanja značajno smanjaju sposobnost materijala za zavarivanje. U radu se opisuje razvoj grešaka kod reparaturog zavarivanja alatnog čelika sa dupleks zaštitom. Nametnuta procedura nastoji smanjiti greške sa novom zavarivnom tehnikom. Proučeni su i efekti različitih parametra procesa i tehnika zavarivanja. Mikrostrukturnim istraživanjima nastoju se naći greške za odabir najboljeg postupka za lasersko zavarivanje alata za dupleks zaštitom.

Ključne riječi: reparaturno zavarivanje, nitrirani alatni čelik, PVD prevlaka, lijevanje u formu

INTRODUCTION

Castings of aluminum and plastics are of high importance in the industrial world. They are usually made using permanent metallic moulds for pressure die-castings and injection molding. Die-tools are usually produced from chromium maraging hot work tool steel and are heat treated to hardness between 29 and 48 HRC, [1-3]. Die life is a mayor factor of a die-casting process and it strongly affects the productivity of mass production. Depending on a cast or mold application, the typical damage and failure mechanisms may differ.

Thermal fatigue cracking is the most important life limiting failure mode in dies for die-casting, [4-6]. Thermal fatigue cracking is often observed on the tool surface as a network of fine cracks or as individual and clearly pronounced cracks [7]. Formation of the thermal fatigue cracks leads to loss of surface material in form of small fragments. Other common reasons for damage are tension cracks caused by constructional notches, local adherence of a casting alloy to the tool i.e. soldering, and steel erosion promoted by the cast molten metal or plastic flow, [8-10]. Molds for plastic injections are subjected to lower working temperatures while pressure cycles are more demanding and, therefore, mechanical fatigue damage and overload failures might occur.

Life of dies can be improved using proper surface treatment, e.g. nitriding, PVD coating, chrome plating, oxidation processes, and duplex-treatments. Plasma nitriding of tools results in easier separation of a product, less frequent cleaning of the die-core system and an increase in service life by 20 % to 50 % [11]. In literature there are reports that plasma nitriding improves thermal fatigue behavior due to high residual stresses in the diffusion layer and improvement of its tempering resistance. It is also reported that thermal cracks remain localized in the compound layer [12]. Oxidation is a process that creates a lubricant oxide film to prevent soldering and adhesive wear in high pressure die casting tools. Hard coating based on nitrides and carbides of transition metals, e.g. CrN, CrC, TiAlN, TiB_2, are also used to protect casting tools surfaces, [13]. The aim of PVD coatings is reduction of erosion, soldering, and corrosion but it was shown that they fail to improve the thermal fatigue resistance of hot working steels in die-casting conditions. None of the above mentioned surface treatments provide an optimum solution for all failure mechanisms,

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[14]. For optimal surface treatments the best choice was proven to be usage of multilayer coatings designed specifically for each application. Each layer in such a structure has a specific purpose.

The increasing demand for manufacturing cost reduction requires exploring adapted and reliable solutions for repairing, and, therefore, extending the life span of the dies. General repair processes are performed by TIG welding or welding with covered electrodes. A contemporary repair approach is laser cladding with a wire, where a laser beam from a pulsed Nd:YAG laser source is focused at the tool surface while an operator adds a filler wire to the molten pool. Laser welding is particularly appreciated owing to the exact positioning and focalization control of the beam allowing elevated accessibility even in thin and narrow areas that cannot be welded conventionally [15]. Because of a locally high density of heat input, laser welded repairs have a greater potential than TIG, especially for welding of distortion-sensitive tools. Repair welding is carried on majority of dies although it is considered critical especially for duplex-treated surfaces. Despite that, repair welding and refurbishing of dies are performed to remove the traces of heat cracking, surface wear, erosion, and stress cracking, thus significantly increasing the tool life cycle [16].

The present work presents problems emerging with laser repair welding of duplex-treated damaged tools without prior to removal of the damaged parts or surfaces by milling or grinding.

EXPERIMENTAL PROCEDURE

The investigations in this paper were carried out on high performance chromium-molybdenum-vanadium alloyed hot-work tool steel DIEVAR (UDDEHOLM) with the following nominal chemical composition (wt. %) of 0,38 C, 0,20 Si, 0,50 Mn, 5,0 Cr, 2,36 Mo, 0,55 V, and Fe balance. Samples were hardened and martempered to achieve hardness of 47 HRC. After tempering some samples were gas-nitrided at 520 °C for 6 h in a NH_3 atmosphere to a depth of around 80 μm and later oxidized at 500 °C for 4 h in H_2/O_2. Some samples were later coated with functional PVD coatings of CrN, TiAlN, and TiN obtained by a reactive sputtering apparatus and in Balzers 730M equipment.

Simulation of repair welding was performed using Nd-YAG laser equipment (Easy welder SLS CL 60) and a filler wire. The filler wire used, i.e. DIEVAR TIG-WELD with 0,5 mm in diameter, is suitable for laser welding. In this paper also effects of the repair welding process parameters for surfaces with different duplex-treatments are investigated. The effects of various laser-pulse shapes and different laser-welding techniques e.g. frequencies, formation sites, and types of weld defects in continuous seam welds are considered. To resolve a pulse shaping effects, the pulse shapes applied were: general, ramped- up, and ramped- down. Table 1 presents the laser welding and surface remelting process conditions. Continuous seam welds were used as a means of bead on plate welding on specimens to understand the effects of pulse shaping and the formation characteristics of weld defects. Also three types of welding techniques were analyzed in order to improve weldability of duplex-treated surfaces. First welding technique designated type A is direct welding. Type B is remelting of whole surface with laser prior to welding and type C where seam covered surface is remelted prior to welding. In Figure 1 all welding types used are shown schematically.

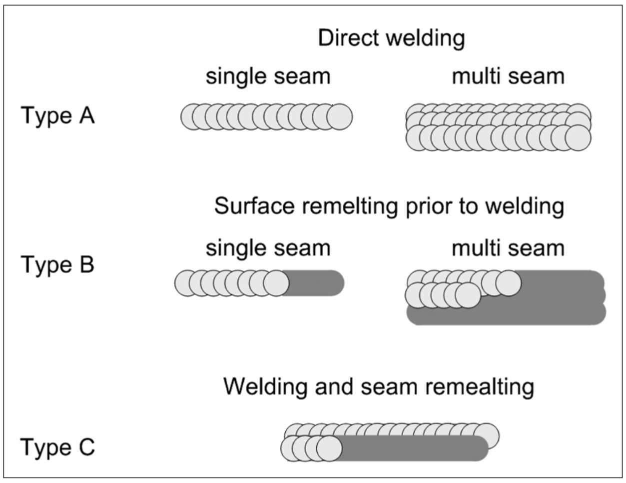

Figure 1. Welding techniques used

To catalogue and characterize errors in the welded layer and the influenced zone for various welding parameters, a metallographic analysis was carried out. Samples for the metallographic analysis were cut with precise cutter, and wire EDM was later polished and

Table 1. **Process conditions for laser welding and remelting**

Pulse shape	General			Ramped up			Ramped down		
Code	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3	No. 1	No. 2	No. 3
Pulse duration /s	$6,5\times10^{-3}$			$6,5\times10^{-3}$			$6,5\times10^{-3}$		
Energy per pulse /J	11,2	12,9	14,9	11,1	13,1	13,2	11,4	12,8	14,4
Pulse power /W	1300	1600	1700	1300	1600	1700	1400	1500	1700
Pulse frequency /Hz	7			7			7		
Spot diameter /m	6×10^{4}			6×10^{4}			6×10^{4}		
Travel speed /ms^{-1}	0,033			0,033			0,033		

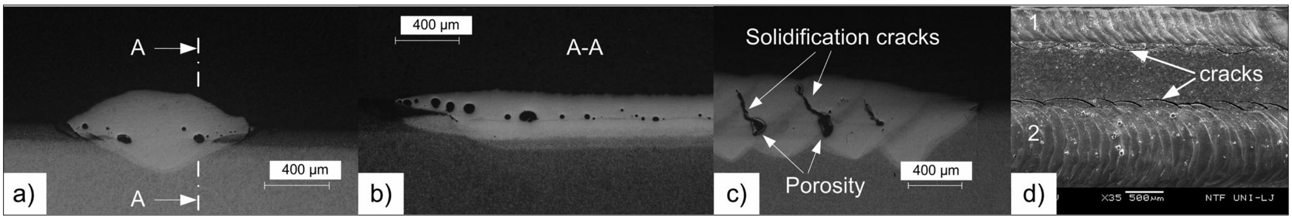

Figure 2. Porosities in duplex treated surfaces after laser welding; a) cross section, b) longitudinal section, c) weld solidification cracks in nitrided and CrN-coated sample, SEM micrograph of cracks along weld

etched in a 2% Nital solution. Observations of prepared samples were carried out by optical microscopy (OM) and scanning electron microscopy (SEM).

RESULTS AND DISSCUSION

The weld analysis of the duplex-treated samples reveals high concentration of pores in weld due to dissolution of gases, e.g. nitrogen, from nitrided layer. Laser, due to localized high energy input, causes abrupt melting and consequently quick solidification. Therefore gases stay trapped at the edges of the weld root. In Figure 2a and 2b weld porosities derived from trapped gases are shown in micrographs of cross and longitudinal sections of nitrided and oxidized surface. The sample was welded using type A technique, ramped-up pulse shape with No. 3 process parameters. Longitudinal section in Figure 2b was analyzed due to higher probability of discovering weld defects in longitudinal sections compared to cross sections.

The micrograph in Figure 2c depicts weld solidification cracks emerging from pores in weld. The sample was nitrided and CrN-coated. High chromium and carbon contents in the filler wire also causes solidification cracks. Welding of nitrided and CrN-coated surfaces is difficult due to formation of cracks at the edges of the heat-affected zone (HAZ) of the weld. These cracks are a consequence of chromium exiting the coating during welding. Their direction of propagation is from pores to apex of the weld.

These types of errors become apparent after additional surface treatments and, therefore, cannot be detected during welding. Similar errors were also present in nitrided and TiN coated samples. SEM micrograph in Figure 2d shows cracks along the seam of a multipass welded nitrided and oxidized sample. Cracks commence due to tensile and compression stress in welds. This is because joining structures thermal expansion coefficients and modulus of elasticity varies. Main causes for these errors at duplex treated surfaces are unsuitable process parameters, e.g. too high heat input or too low a welding velocity.

Influence of process parameters, welding technique and pulse shape on the porosity rate of weld is depicted in Figure 3. As shown, remelting of surface prior to welding causes smaller porosity rate compared to direct welding of duplex-treated surfaces. Furthermore, type C

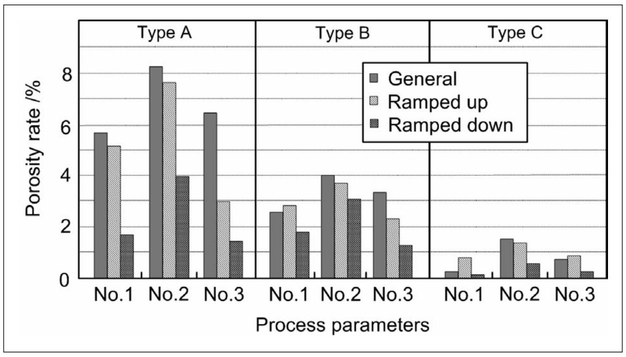

Figure 3. Influence of process parameters, welding technique and pulse shape on porosity rate of weld

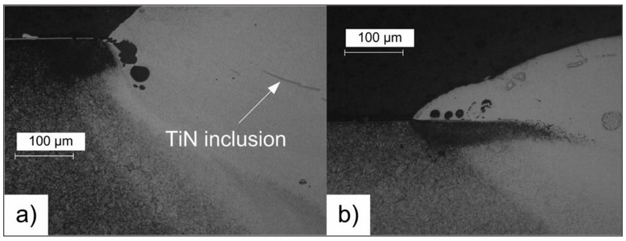

Figure 4. Laser welds on duplex-treated surfaces; a) nitrided and TiN-coated surface, b) nitrided and CrN-coated surface

welding, where each seam is fractionally remelted, has lowest porosity rate. Also process parameters of the welder and pulse shape are of high importance. It is shown, that ramped-down pulse is superior compared to general or ramped-up one, however, appearance of low weld fusion penetration or adherence of weld material to some sections is noticed. Higher pulse energy leads to declined porosity density in the weld. An increase of pulse power leads to solidification cracks in welded joint and amassment of cracks in duplex-treated surfaces. Energy per pulse and pulse power must be chosen specifically for differently treated surfaces. Prior trials on samples before repairing real dies are suggested.

Figure 4a depicts traces of TiN coating in a welded material and porosities at the boundary between the weld and the surface. Distribution of TiN inclusions in weld is problematic due to an increase of tool wear. Figure 4b presents welded nitride and CrN surface using an inclined beam and type C technique.

Appearance of cracks at a contact of the weld and the base material is undesired. Positions of these errors present danger for peeling-off of weld and duplex-treated surface layers, especially at nitrided and oxidized surfaces. Cracking can be reduced with manipulation of laser beam parameters or with inclination of the beam. Usage of beam inclination causes a tampon region, which makes excessive cracking of treated surface impossible. It is possible to prevent excess nitrogen evaporation with manipulation of welding parameters. Welding parameters are also important for minimizing the effect of transitional elements exiting coatings, especially at multi-seam welding.

Repair welding of duplex treated samples leads to copious development of gas porosity due to nitrogen release from molten nitrided part of surface or exiting of transitional elements from coatings. Inclusions from coatings in welds also cause problems and are therefore undesired. The laser remelting treatment before weld deposition was investigated in order to reduce welding errors. The results suggest that using the type C welding technique and close observation of the welding process parameters minimizes the porosity rate at duplex-treated surfaces.

CONCLUSIONS

The main findings of the presented research can be summarized as follows:

Special attention should be paid to the first surfacing weld adjacent to the duplex-treated surface. Lower-power laser beams and the ramped-up pulse shape should be used in order to reduce the level of surface cracking that may subsequently produce peeling-off of the tool surface.

The lowest density of porosity is obtained with the ramped-down shape of a laser pulse and a sufficiently high energy permitting complete remelting of the nitrided layer.

A combination of welding and preliminary remelting i.e. type B, however, reduces the occurrence of defects, e.g. inclusions and pores, in the surfaced layer, yet this does not provide optimum results since, due to melt spatter, nitride inclusions will persist at the surface and thus pass on to the surfaced layer.

The occurrence of inclusions, i.e. rests of melted PVD claddings, can be reduced by using "Leading-power spike", which will produce evaporation of the cladding.

The newly developed process of simultaneous remelting i.e. type C, in combination with a falling pulse results in the lowest density of defects in a surfacing weld, the welding time being shortened.

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