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MICROSTRUCTURAL EVOLUTION OF A COLD WORK TOOL STEEL AFTER PULSED LASER REMELTING

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The aim of this study is the investigation of micro-structural behaviour of a Mat. No. 1.2379 (EN-X160CrMoV121; AISI D2) cold work tool steel after remelting with a precise pulsed Nd:YAG laser. The investigated steel is one of the most hard to weld tool steels, due to large amount of alloying elements. The analysis was done on single spots remelted with specific laser pulse shape and parameters, assuring crack-less solidification. Re-solidified areas were investigated with microscopy, hardness measurements, X-ray spectroscopy and diffraction method. Laser treatment causes rapid solidification leading into a formation of a fine dendritic microstructures containing high amount of retained austenite causing a significant decrease of hardness.

Key words: laser, welding, microstructure, tool steel

Procjena mikrostrukture alatnog čelika za hladni rad nakon pretaljivanja pulsirajućim laserom. Namjena ove studije je ispitivanje ponašanja mikro strukture alatnoga čelika za rad na hladno Mat. No.1.2379 (EN-X160CrMoV121; AISI D2) po pretaljivanju s preciznim pulsiranim Nd:YAG laserom. Zbog velike količine legirnih elemenata istraživani materijal spada u grupu vrlo teško zavarljivih alatnih čelika. Analiza je provedena na pojedinim pretaljenim točkama korištenjem specifičnog oblika i parametara laserskog impulsa koji osiguravaju skrućivanje bez pukotina. Pretaljena područja su ispitivana mikroskopom, mjerenjem mikro tvrdoće, rendgenskom spektroskopijom i defrakcijskom metodom. Tretman laserom uzrokvao je brzo skrućivanje koja dovodi do formiranja fine dendritičke strukture s velikim udjelom zaostalog austenita što uzrokuje bitno smanjivanje tvrdoće.

Ključne riječi: laser, zavarivanje, mikrostrukture, alatni čelik

INTRODUCTION

Repair by cladding is a common and standard practice in the die and mould industries. The life of loaded die elements and vital tool parts can be successfully extended by the timely repair of damaged surfaces. The main advantages of repair using the cladding procedure are well known: a short down-time and economic advantage compared to machining a new tool or die part [1,2].

For distortion sensitive tools, high-density heat input processes such as electron beam and laser beam welding are preferred. Laser-deposit welding, using modern Nd-YAG lasers, is a very flexible process, with the advantage relatively to the traditional methods (micro-plasma and TIG) [3-5].

After the laser treatment, the surface properties are determined by the final structure-phase states [6]. According to literature research there is limited amount of work concentrated on detailed microstructure characterization of laser treated 1.2379 steel.

Steels of this type contain a massive amount of carbides, which make them very difficult to weld. It is preferable to weld them in the annealed condition whenever feasible. In order to avoid cracking and excessive residual stresses induced by welding, pre-heating and post-weld heat treatment are generally carried out [7]. Our previous study has, for example, shown that the high-carbon, high-chromium cold-work tool steel can be successfully remelted or welded in cold [8]. This can be carried out with a specific laser pulse shape and parameters only. However, the detailed investigations of the structure and phase evolutions in particular steel is still missing. The purpose of this work is therefore to study the microstructures and phase transformations in the laser melted spots of the 1.2379 tool steel.

EXPERIMENTAL PROCEDURE

Material

A cold-work die steel, Mat. No. 1.2379 (AISI D2), was studied in this work. Its chemical composition and transformation temperatures are shown in Table 1. Before the laser beam treatment, samples were machined to dimensions of 15 × 10 × 100 mm. The bars were vacuum-quenched and tempered to achieve hardness of approx. 670 HV.

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Table 1 **Composition and transformation temperature of the specimens**

Material	Chemical composition / wt.%								Transformation Temperature / °C			
	C	Si	Mn	Cr	Mo	V	Fe		Ac_1	Ac_m	Ar_1	Ms
1,2379	1,40 to 1,60	0,35	0,40	11 to 13	0,7 to 1,20	0,85	bal.		810	982	760	230

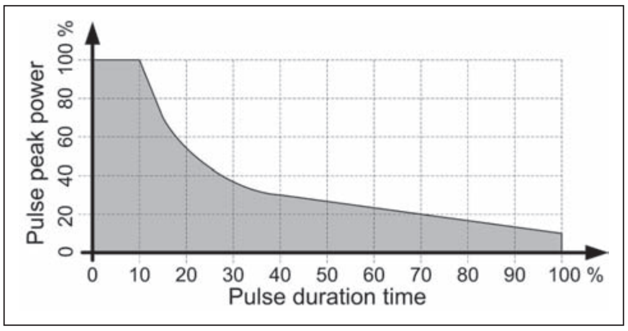

Figure 1 The ramped – down laser pulse shape used for remelting

Laser treatment

Laser remelting was performed using pulsed 200 W laser equipment (Lasag Easy welder SLS CL 60). Argon gas 5.0 with flow rate of 8 l/min was used for shielding. For the experiment the long ramped-down pulse shape (Figure 1), assuring crack-less remelting was chosen. The values of laser parameters are presented in Table 2.

Table 2 **Values of laser parameters**

Parameter	Value
Focal length / mm	160
Pulse peak power / kW	1
Pulse duration time / ms	60
Pulse energy / J	21,6
Gas flow rate / l/min	8

Analysis

Samples for the metallographic analysis were sectioned with a precision cutter, polished and etched with 4 % Nital solution (for optical microscopy - OM) and Vilella's solution (for scanning electron microscopy - SEM). Examination of prepared samples was done using OM (Olympus GX-51), SEM (Jeol JSM-5610), micro-hardness measurements (Leitz MINILOAD 2) and XRD (Bruker D8 Advance with Cu radiation) analysis.

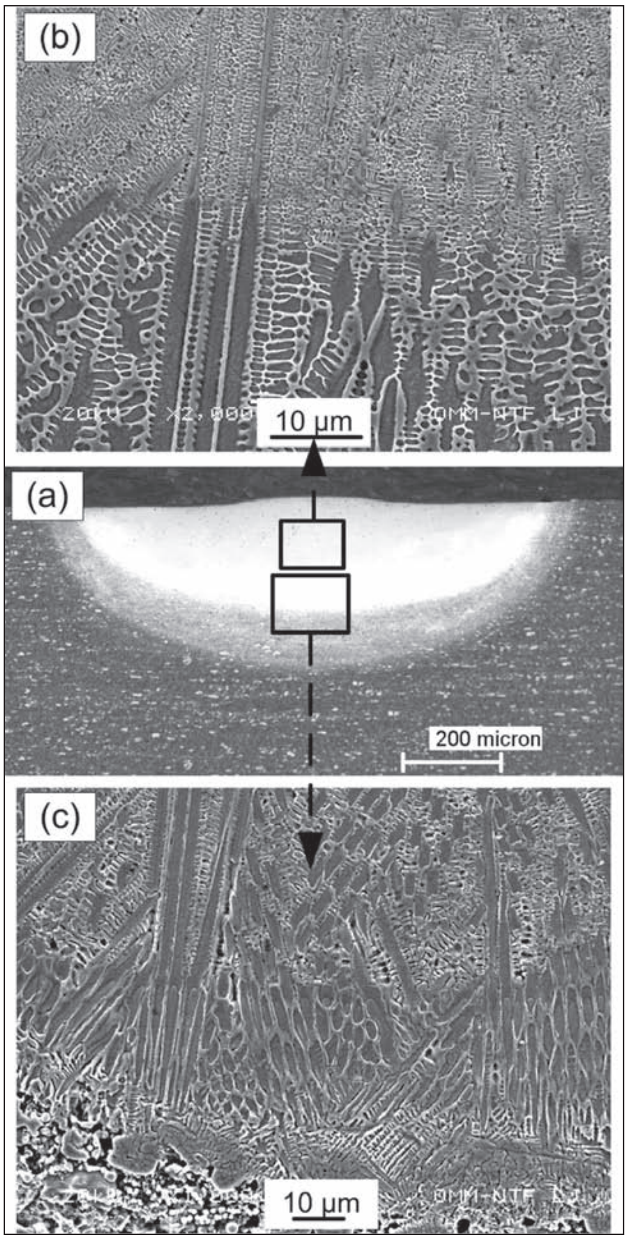

Figure 2 Cross-section of remelted spot: OM macrograph a), detailed SEM micrograph of fusion area b) and transitional area c).

RESULTS AND DISCUSION

Typical macrostructure of the sample after treatment is shown in Figure 2 a and 3 a. The untreated material (surrounding the remelted spot) presents an inhomogeneous distribution of large-sized carbides having different shapes. In the optical micrograph (Figure 2 a), these carbides are visible as white blocky shapes. They are rich in Cr and cannot be easily etched. In contrast to the base material, the microstructure formed in the melted and re-solidified spot consists mainly of very elongated grains, extending from the pool boundary to the surface and minor portion of equiaxial grain in the spot center.

When welding without a filler metal or at remelting, nucleation occurs by arranging atoms from the liquid metal upon the substrate grains without altering their existing crystallographic orientations. During weld metal solidification, grains tend to grow in the direction perpendicular to pool boundary, because this is the direction of the maximum temperature gradient and hence maximum heat extraction. However, columnar dendrites or cells within each grain tend to grow in the easy-growth direction [9]. Therefore, during solidification grains with their easy-growth direction essentially perpendicular to the pool boundary will grow more easily and crowd out those less favourably oriented grains.

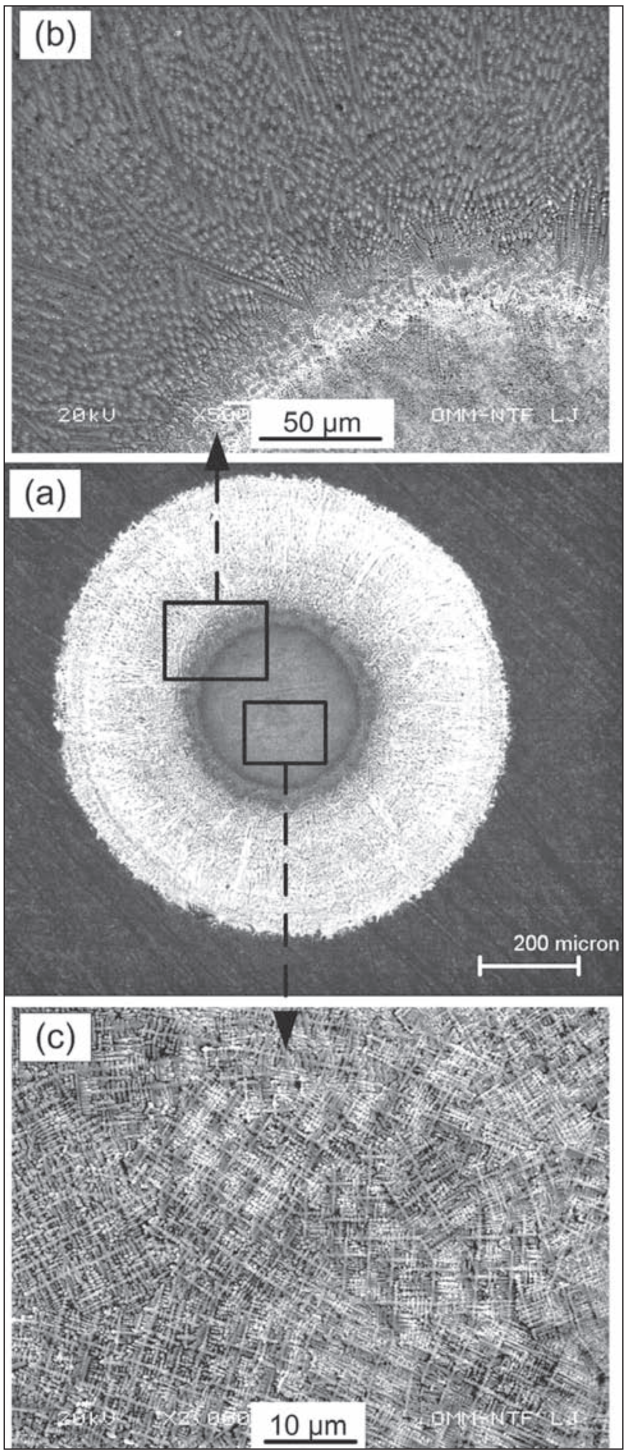

Figure 3 Images of remelted spot face: OM macrograph a), detailed SEM micrograph of transitional area b) and spot center c).

The microstructure within grains consists of columnar dendrites at the fusion line (Figure 2c) that become very fine towards the spot center (Figure 2 b and 3 b) where also equiaxial dendritic microstructure occurs (Figure 3 c). The microstructures within the grains depend on solidification mode, which is influenced by the degree of constitutional supercooling. The solidification mode changes from planar to cellular, columnar dendritic, and equiaxed dendritic as the degree of constitutional supercooling at the pool boundary increases (Figure 4) [9]. The change in the solidification mode in our case occurs due to a specific laser pulse action, where the relatively long pulse duration time ensures an appropriate thermal regime for the formation of grains with fine columnar and equiaxial dendritic microstructure.

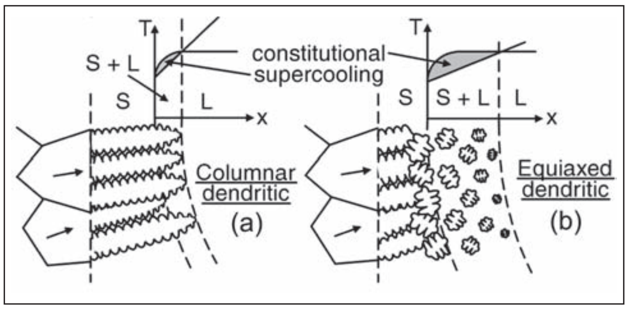

Figure 4 Effect of constitutional supercooling on solidification mode: columnar dendritic a), equiaxed dendritic b) [9].

The micro-hardness measurements reveal some unexpected results. Regarding the chemical composition of base material, high hardness (over 800 HV), due to remelting and consequently self-quenching would be expected. The horizontal measurement was made on a depth of 100 μm. As it can be seen from a diagram in Figure 5, the hardness measurements in remelted area are very low and amount between 480 and 510 HV. That is over 100 HV less than in the base material which was tempered to approx. 620 HV (56 HRc). The vertical measurement (Figure 5a) exhibits some minor differences in the area right below the surface. In this approx. 80 μm deep central area the hardness values amount 540 HV. This can be related to the fine dendritic microstructure. The highest hardness of up to 850 HV was measured in the heat affected zone (HAZ) that is in horizontal direction 100 μm wide and in vertical approx. 150 μm wide. High values of hardness in HAZ were expected due to remelting without preheating and consequently high cooling rate.

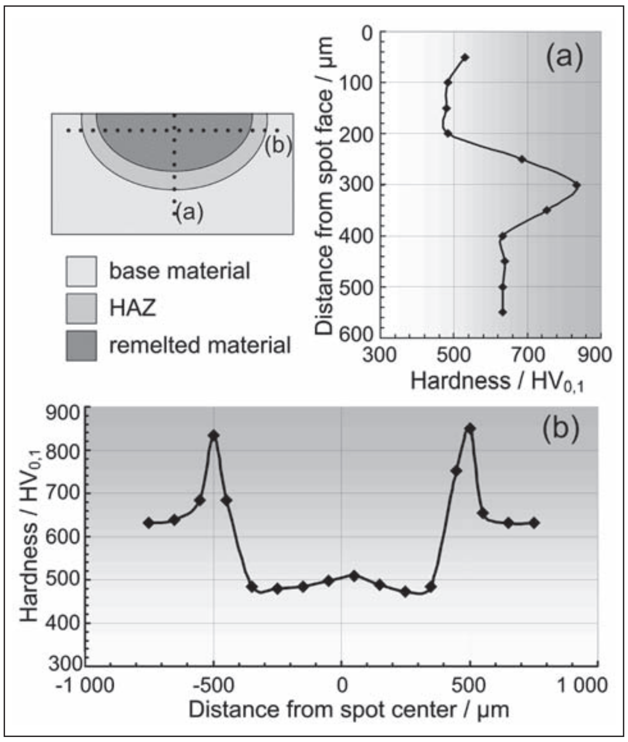

Figure 5 Micro-hardness measurements in the remelted spot: vertical direction a), horizontal direction b).

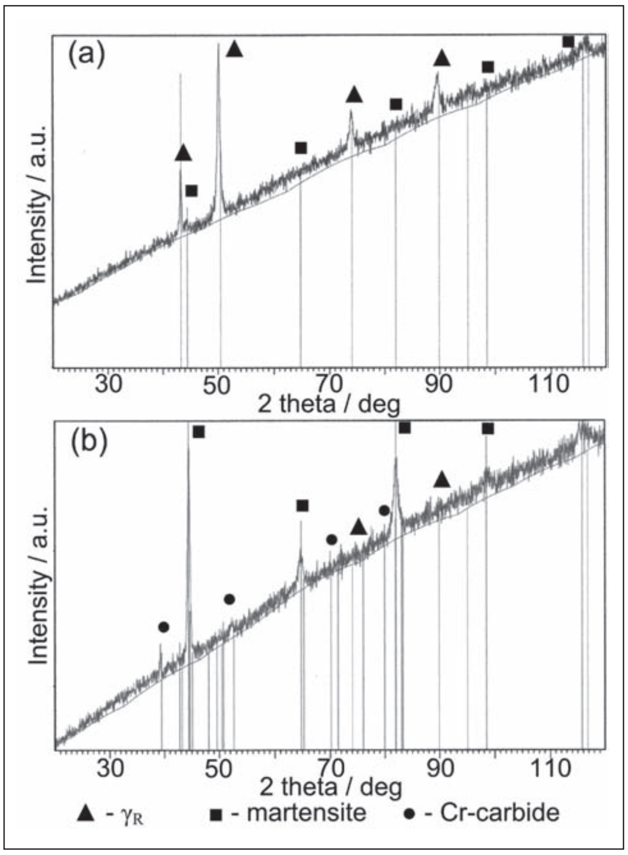

Figure 6 XRD diffractograms: laser treated sample a), initial sample b).

From the Figure 6 it can be inferred that such unusual micro-hardness values could be caused by a formation of retained austenite (γ_R) phase. This phase can occur as a result of (1) high solidification rate during laser surface melting. and (2) due to the higher cooling rate at which the higher portion of retained austenite is formed [10]. The portion of phases in remelted material is presented in the diffractogram in Figure 6a. It reveals the peaks of martensite and peaks of austenite. The calculated portion of γ_R amounts 41,6 %. In our case, the γ-phase grows directly from the melt during the rapid solidification process. The high Cr and C content in this phase is an important factor for depressing the M_s temperature [11].

For a comparison, the XRD analysis was carried out on samples before the laser treatment (Figure 6 b). The initial sample mainly contained two phases: ferrite/martensite (α-Fe) and carbide Cr_7C_3. The peaks of the Cr-carbides disappeared after the laser treatment. Some partially dissoluted carbides can be found by the fusion zone only (Figure 7), while the rest of this phase in the bulk dissolutes completely.

CONCLUSIONS

Pulsed laser remelting creates very interesting and intriguing surface modifications. The following findings of this research can be summarized:

- A formation of very elongated columnar grains with the minor portion of equiaxial grains in the spot center occurs during re-solidification.

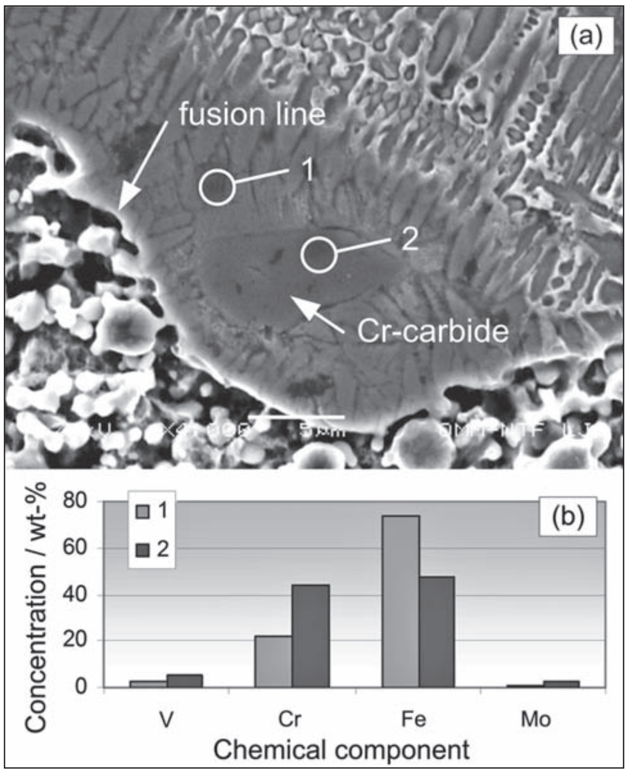

Figure 7 Image of the Cr-carbide at the fusion line a), chemical micro-analysis b).

- The microstructure within grains consists of columnar dendrites, growing from the fusion line. They become ultrafine towards the spot center.
- The hardness measurements revealed a significant decrease of hardness in the melted volume. This is related to a formation of retained austenite during rapid cooling.

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