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Microstructure and abrasive wear behavior of a novel FeCrMoVC laser cladding alloy for high-performance tool steels

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ABSTRACT

This work shows the successful application of a novel Fe85Cr4Mo8V2C1 (wt%) laser cladding wire material on a high-performance tool steel (1.2379, X155CrMo12-1) using a pulsed Nd:YAG laser system. Due to the high cooling rates during the welding process and appropriate laser parameters, a fine, homogeneous microstructure composed of martensite, austenite as well as VC- and Mo_2C-type carbides was formed. This combination of phases along with their special morphology and distribution result in crack-free dense coatings with an enhanced hardness and abrasive wear resistance compared to the substrate material and a conventionally applied cladding alloy. In summary, laser cladding with the novel FeCrMoVC alloy shows a high potential for repair welding and hardfacing of high-performance carbon-rich steel tools.

1. Introduction

Laser cladding occupies a key position in modern tool manufacturing. The increasing processing of high-strength alloys and composites results in reduced lifetimes of the tools. Cold-work tool steels containing high carbon and chromium contents (like the high-performance 1.2379 steel) are commonly applied for cutting devices, forming dies, molds and other components, which have to sustain extremely high loadings and severe wear conditions [1–3]. Especially in the plastics processing industry, polymers with very hard fillers like corundum lead to aggressively abrasive wear conditions for the tools [4,5]. In order to extend their service life, repair welding as well as hardfacing of highly loaded tool parts provides a cost-saving and resource-efficient alternative compared to continuous acquisition of new tools. In particular, for repair purposes the manual laser cladding by using very thin wires is a favorable method. Thereby, worn areas of complex profiles and broken edges of localized geometries can be rebuilt [6].

However, for laser cladding of high carbon tool steels, only a few wire materials are described in literature and are commercially available. The related great challenges during processing due to a high susceptibility to cracking are known [6–9]. Generally, the quality of generated coatings can be determined by a tailored alloy design and defined processing parameters for the appropriate substrate material [7,8,10,11]. In terms of hardly weldable tool steels, the substrate can be heated during the welding process or the finished welded part is additionally heat-treated to avoid the formation of cracks [12,13], which is time-consuming and cost-intensive. Consequently, especially for repair purposes of high carbon steels (e.g. 1.2379 steel) it is resorted to use cladding alloys with distinctly lower carbon contents as the substrate resulting in a reduced hardness and abrasive wear resistance [7,14] but guaranteeing a good weldability without obviously visible cracking of the coating or the substrate. This demonstrates clearly that novel cladding materials are required combining a good weldability with a resulting hard and high abrasive wear-resistant clad.

For low carbon steels as substrate, a high resistance against abrasion due to laser cladding with commercial and modified Fe-based alloys was already extensively described [12,15–20]. These investigations reveal a correlation between the microstructure of the coatings and their wear behavior under abrasive conditions. The abrasive wear resistance depends mainly on the morphology and properties of the phase constituents of the coatings. Thereby, especially the type, shape, size, distribution and volume fraction of dispersed carbides play an important role [12,15,18,19]. Furthermore, the residual stress distribution may influence the impact toughness of the coated substrate. A compressive residual stress state is assumed to be beneficial for preventing crack initiation and propagation [21–23].

The present study describes the application of the novel Fe85Cr4Mo8V2C1 (wt%) steel as a cladding material for the high carbon cold-work 1.2379 tool steel. The FeCrMoVC alloy was already characterized and applied as tool material in the as-cast state due to its

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high strength and adequate ductility under compressive load as well as its high hardness and good wear resistance without any subsequent heat-treatment [24–26]. Previous studies showed a good processability by laser welding technology building up complex geometries and filigree structures without pre- or postheating of the substrate [27]. However, the behavior of the alloy as a cladding material for laser deposition and repair welding has not been studied, yet. Therefore, the aim of the present work is to examine the effect of the very fast solidification realized during the laser cladding process on the microstructure and resulting properties of the novel FeCrMoVC wire material applied on the high-performance cold-work 1.2379 tool steel as substrate using a manually guided pulsed laser system. Intensive investigations regarding the content and morphology of the existing phases on the hardness and abrasive wear behavior are done. Furthermore, the novel cladding alloy is compared to a conventionally applied cladding material commonly used for repair purposes [7,14].

2. Materials and methods

Before implementing the FeCrMoVC alloy as a novel cladding material, thin wires were produced by a self-developed forming process. Afterwards, the new material and the 1.4718 steel (X45CrSi9-3), both in form of thin wires with a diameter of 0.6 mm, were used to produce coatings on the cold-work 1.2379 tool steel (X155CrMo12-1) by an industrial manual laser cladding process, whereby the operator guides the wire material by hand. The substrate material was hardened and tempered to achieve a final hardness of 54.1 ± 0.5 HRC. Then it was cut into specimens with the dimensions of (30 × 30 x 20) mm^3. The nominal chemical compositions of the materials are displayed in Table 1. The chemical composition of the new FeCrMoVC alloy was confirmed by the use of carrier gas hot extraction (EMIA 820 V, Horiba) for detecting the carbon content and inductively coupled plasma optical emission spectroscopy (IRIS Intrepid II XUV, Thermo Fisher Scientific) for determining the other elements.

Laser cladding was carried out using a pulsed Nd:YAG laser (TruPulse 556, TRUMPF) with a mean power of 530 W without any pre- or postheating treatment of the substrate. For the experiments, the laser was operated at a fixed average power of 166.5 W and a focus of 1.15 mm. The pulse frequency was 9 Hz. During the welding process argon was used to provide shielding from ambient air. By welding three layers on the substrate the coatings attained a total thickness of about 0.9 mm.

The measurement of mean residual stresses in the clad were conducted by Siempelkamp Prüf- und Gutachtergesellschaft mbH (Dresden, Germany) applying the hole-drilling method according to ASTM E 837-13a. Strain gauge rosettes (K-RY61-1,5/120R-2-0,5 m) were placed on the center of the surface with a clad coverage of (20 × 20) mm^2. Using the high speed air turbine mill and strain measurement system MTS 3000 (Hottinger Baldwin Messtechnik GmbH) a diamond drill generated a cylindrical hole with a diameter of 1.8 mm and a depth of 0.8 mm. By measuring the relieved strains during drilling the principal residual stresses in longitudinal direction σ_L (parallel to the laser cladding path) and in transverse direction σ_T (perpendicular to the laser cladding path) were calculated and averaged over the penetration depth. For the evaluation, values of Young's modulus $E = 210$ GPa and Poisson's ratio $\nu = 0.3$ were used. A relative uncertainty of measurement of ± 20 N/mm^2 was determined.

To investigate the microstructure of the laser cladded surfaces, Nital etched samples were examined by optical microscopy (OM; VHX2000, Keyence) and scanning electron microscopy (SEM; Zeiss Leo 1530 Gemini). Phase identification was conducted by X-ray diffraction (XRD; STOE Stadi P, Mo $K_{\alpha 1}$ radiation) and by subsequent Rietveld analysis [28] using FullProf [29]. The microhardness on the cross sections was determined with a Vickers microhardness testing system (HMV-2, Shimadzu) applying a force of 1 N.

The abrasive wear behavior was studied by performing pin-on-disk tests according to ASTM G132-96 and DIN EN 1071-13, respectively. For the experiments, pins made of the cold-work steel were laser cladded by the examined Fe-based alloys (Table 1) and prepared by mechanical grinding using SiC grinding paper with a final finish of 1200 grit (P4000). The initial dimensions of the cylindrical, coplanar pins were 6 mm in diameter and 15 mm in length. The counter-face was a rotating abrasive disc made of white corundum with a mean particle size of 470 µm. By using a tribometer (T500, Nanovea) a normal load F_N of 20 N was applied on the pins, which run a total sliding distance L of 20.7 m on a spiral with no overlapping track and a rotation speed of 100 rpm at room temperature. According to DIN EN 1071-13 the wear rate k was calculated as follows:

$$k = V/(F_N \bullet L). \tag{1}$$

The wear volume V was hereby determined for every tested sample by $V = (m_0 - m) / \rho$, whereby m_0 is the mass of the steel pin before the wear test and m the mass after testing. The density ρ was determined based on the Archimedean principle (density determination kit; YDK 01, Sartorius). At least eight specimens of each steel modification were tested and the corresponding average wear rate and related standard deviation were determined. Furthermore, SEM and microhardness measurements were performed to study the characteristics of the worn surfaces of the pins and to determine the appearing wear mechanisms.

3. Results and discussion

3.1. Microstructure

Fig. 1 shows SEM micrographs showing the individual characteristic microstructure of the investigated laser clads (Fig. 1a-d) and the substrate alloy (Fig. 1e, f). Preliminary microscopic examinations on the FeCrMoVC coatings revealed no cracks or discontinuities leading to uniform deposition layers on the substrate. The microstructure consists of fine columnar dendrites indicating high solidification rates during the laser cladding process (Fig. 1a). Solidification rates of 10^4 to 10^5 K/s are estimated from the distance of an averaged secondary dendrite arm spacing of about 1 µm [30,31]. Martensite is partially present in the austenitic dendrites. Due to self-quenching a part of the solidified austenitic dendrites transforms into martensite during cooling. Higher magnifications uncover the presence of interdendritic primary carbides, which are formed in a complex network-like structure. Fig. 1b demonstrates carbides of compact and lamellar types with a size of 200 to 500 nm and 200 nm up to 1 µm, respectively. In contrast to the FeCrMoVC microstructure the 1.4718 laser clad exhibits a homogeneous mixture of martensitic and austenitic phase, whereby no carbides

Table 1
Chemical compositions of the laser cladding alloys (FeCrMoVC, 1.4718) and the substrate (1.2379).

Materials		Fe	Cr	Mn	Mo	Si	V	C	Other
FeCrMoVC	Nominal (wt%)	85	4	–	8	–	2	1	–
	Real (wt%)	84.51 ± 0.09	3.64 ± 0.01	–	8.43 ± 0.02	–	2.11 ± 0.00	1.02 ± 0.00	–
1.4718	Nominal (wt%)	86.5	9.5	0.5	–	3.0	–	0.5	Cu, Ni < 1
1.2379 (substrate)	Nominal (wt%)	84.05	12	0.4	0.85	0.35	0.85	1.525	Co, W, Ni, Cu < 1