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Experimental Characterization of Clad Microstructure and its Correlation with Residual Stresses

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Abstract

The repair of dies and molds used in the automobile industry by laser cladding (LC) is an important and emerging trend in additive manufacturing (AM) today. LC provides an alternative to the traditional deposition techniques which are ad-hoc and imprecise for powder metallurgical steels used in the repair of these components. The current study focuses on understanding the correlation between microstructure and the residual stress developed due to the deposition process. The microstructure was characterized using Electron Backscatter Diffraction (EBSD) analysis and the residual stress was measured using micro focus X-ray diffraction technique. The EBSD study revealed that the relative difference in martensite phase fraction resulted in local grain misorientations. A thermomechanical finite element (FE) model was also developed to predict the magnitude and nature of residual stresses in the component. The FE model calculated the stress field by considering only the thermal strain developed between the clad and substrate layers. The FE model was able to capture the nature of residual stresses in the clad and substrate where the thermomechanical effects dominate. The study revealed the importance of incorporating the effect of metallurgical transformation in FE model to accurately predict the residual stress variation in the substrate region.

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Keywords: Laser cladding; repair; EBSD; X-ray diffraction; thermomechanical finite element model

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1. Introduction

The localized damage of molds and dies used in hot and cold working industry due to cyclic thermomechanical loading is a matter of serious concern [1-3]. Over the years, it has been observed that repairing these dies and molds with Crucible Particle Metallurgy (CPM) steels can potentially address the existing difficulty of excessive localized damage during operation [1, 4]. CPM steels are a special class of steels which have high weight percentage of vanadium and more uniform distribution of finer size carbides. Thus, the carbide segregation can be avoided which results in excellent combination of toughness, hardness and wear resistance as compared with conventional ingot cast tool steels [5]. Traditional repair techniques, such as thermal spraying, are ad-hoc and imprecise for these CPM steels. Moreover, the inherent issues with traditional repair techniques can lead to thermal damage and distortion of the finished component [3]. In addition to this, the dies and molds have complex 3-D shapes and they call for a very precise contoured deposition so as to avoid high tensile residual stresses. Therefore, a precise and focused thermal energy transfer process is required for the repair of these components. In this regard, a laser-based deposition technology, such as laser cladding, characterized by localized heating and rapid fusion of materials, is a promising technique.

Laser Cladding (LC) or Laser Engineered Net Shaping (LENS) are defined as Directed Energy Deposition processes, according to ASTM F42 standard [6], in which multiple layers of clad are deposited over a substrate (see Figure 1(a)). A strong interfacial bond with minimum dilution between the material layers is a pre-requisite of the process [7]. This is because clad dilution, which in generally is considered as contamination of deposited layer with the substrate material, can alter the mechanical and metallurgical properties of the clad. Moreover, laser cladding generates a relatively narrow dilution and heat affected zone (HAZ) [8, 9]. Several physical phenomena influence the quality and integrity of the final cladded component. These are the melt pool morphology, microstructure evolution and residual stress generation [3, 4, 10-12]. Characterization of microstructure of the clad, dilution, heat affected zone and substrate has been extensively reported in literature. However, these studies have been mainly restricted to Tungsten Carbide-Cobalt powder [13], Stellite 12 [14], Stellite 6 and Tungsten Carbide [15-17]. In addition to the above microstructural analysis of various metal matrix composite (MMC) such as metallic tool steel M2, Stellite 21, NiCrBSi-alloy and Inconel 625 [18] and selective laser melting (SLM) [19] has also been reported. These studies have reported phase and elemental investigation, using Energy dispersive scattering (EDS) and X-ray diffraction analysis along with micro-hardness analysis.

Apart from microstructural analysis, the residual stress in the finished components is of immense importance. This is evident from the fact that tensile residual stresses in the clad layer or clad-substrate interface region can lead to accelerated fatigue failure [1, 3]. The importance of metallurgical transformation of metallic alloys on residual stress can be understood from the fact that in metallic alloys liquid-solid transformation, formation of second phase particles and displacive transformations occur. Limited work has been reported in literature to investigate the effect of process parameters on residual stresses being developed in the laser cladded components using X-ray and synchrotron diffraction techniques [20], Neutron diffraction [21] for Cobalt-chromium alloys. However, comprehensive residual stress characterization and modelling for CPM steels has not been reported in the literature. Therefore, it is important to understand the causes for evolution of residual stresses in a laser cladded component and their relationship with microstructural transformation for CPM steels. Accordingly, this study is aimed at correlating the effect of metallurgical transformation such as phase evolution and associated grain misorientation on the residual stress developed during laser cladding of H13 tool steels using CPM 9V steel powders.

In addition to experimental characterization, it is desirable to develop Finite element (FE) models to predict the clad quality as a function of process parameters and identify the optimal cladding conditions. This is because FE model is an appropriate tool to estimate the temperature distribution, and characterize the clad quality, which includes clad dilution, HAZ, microstructure evolution and residual stress field. As LC is a temperature driven melting and solidification process [9], the residual stress primarily develops due to differential thermal expansion and subsequent contraction between the clad and substrate layers [4]. Various transient stress analysis for non-powder metallurgical material systems, such as titanium alloy [22], stellite on austenitic stainless steel AISI 304 [23] and monel on Ni-based alloys [24] have been presented in literature. In addition to these, thermal analysis to investigate the effect of surface tension on the melt pool in laser cladding of CPM steels [12] has also been reported. Pal *et al.* [25] has reported 3D dislocation density based thermomechanical finite element analysis for SLM. FE