Materials Science and Engineering A 527 (2010) 7265–7273

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Experimental study of residual stresses in laser clad AISI P20 tool steel on pre-hardened wrought P20 substrate

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ARTICLE INFO

Article history:
Received 7 February 2010
Received in revised form 11 July 2010
Accepted 29 July 2010

Keywords:
Laser cladding
AISI P20 tool steel
Residual stress
Neutron diffraction
Hole-drilling method
Tooling repair

ABSTRACT

Laser cladding is to deposit desired material onto the surface of a base material (or substrate) with a relatively low heat input to form a metallurgically sound and dense clad. This process has been successfully applied for repairing damaged high-value tooling to reduce their through-life cost. However, laser cladding, which needs to melt a small amount of a substrate along with cladding material, inevitably introduces residual stresses in both clad and substrate. The tensile residual stresses in the clad could adversely affect mechanical performance of the substrate being deposited. This paper presents an experimental study on process-induced residual stresses in laser clad AISI P20 tool steel onto pre-hardened wrought P20 base material and the correlation with microstructures using hole-drilling and neutron diffraction methods. Combined with X-ray diffraction and scanning electron microscopic analyses, the roles of solid-state phase transformations in the clad and heat-affected zone (HAZ) of the substrate during cladding and post-cladding heat treatments on the development and controllability of residual stresses in the P20 clad have been investigated, and the results could be beneficial to more effective repair of damaged plastic injection molds made by P20 tool steel.

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1. Introduction

Laser cladding by blown powder or wire feeding can deposit a layer of material onto the surface of a similar or dissimilar base material (or substrate) to produce a metallurgically sound and dense clad. In the last 20 years, many relevant applications have been reported [1–3], the majority of which, can be divided into two areas: (1) laser cladding to deposit high-performance material on high-value component or tooling made by different base material to enhance its local (or entire) surface properties, such as the resistance against corrosion, wear, or high-temperature oxidation, etc.; the component or tooling made by the above hybrid materials can provide an overall mechanical performance which no single material can provide and in addition, they often can save overall costs of raw materials and manufacturing process by allowing optimal material to be used in needed location(s), and (2) laser cladding (or laser cladding base free-form fabrication) to repair or restore original geometries and functionalities of a worn or damaged high-value component or tooling and sometimes, to restore undersized expensive material due to machining or grinding errors. It is no doubt that other alternative processes are also available for the similar applications such as TIG welding, thermal spraying, gas dynamic spraying (GDS), e-beam deposition and others. Considering various factors relevant to the costs of materials, equipment and manufacturing processes, and the quality of deposited materials, laser cladding has demonstrated some unique advantages over others: it can produce metallurgically sound and dense clad layer using a relatively low heat input which minimizes the distortion of the component or tooling being deposited; it produces metallurgical bond between the clad layer and the substrate; and it can control the dilution of cladding material into the substrate to reduce undesired deterioration of mechanical properties of the base material. The National Research Council's Industrial Materials Institute (NRC-IMI-London) has been developing laser cladding base processes for more than a decade, targeting at automotive, aerospace and other manufacturing industrial applications [4–8].

The objective of present research aims at laser cladding to deposit AISI P20 tool steel onto pre-hardened wrought AISI P20 substrate for the purpose of repairing and restoring damaged tooling. The P20, a kind of low carbon tool steel containing chromium and molybdenum alloying elements, is commonly used for making plastic injection molds. The P20 tool steel is thermally hardenable through proper heat treatments [9], providing a reasonably good wear and corrosion resistances. The plastic injection molds made by P20 tool steel, however, still frequently require some forms of repair by welding [10] because of the damages/worn-out in the molds, the errors in machining or the changes in design required during manufacturing. Laser cladding has been identified as a promising

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doi:10.1016/j.msea.2010.07.098

process for repairing and restoring original dimensions and functionalities of those molds to extend their service life and in addition, for enhancing or re-configuring existing molds for their subsequent re-use, to substantially reduce their through-life costs [11].

Nevertheless, it should be realized that laser cladding of tool steels, in spite of relatively low heat input, still need melt a small portion of base material (or substrate) along with cladding material, which would introduce certain amount of residual stresses in both clad and substrate. It is well known that residual stresses, defined as intrinsic self-equilibrating stresses, exist without external forces. They arise as consequences of various thermal treatments, which cause thermal gradients and phase transformations, as well as of thermo-mechanical processing, which causes local elastic or plastic deformation [12]. For laser cladding process, in general, the major causes of process-induced residual stresses in a clad layer are ascribed to two effects [11,13–15]: (1) thermal mismatch among the clad, the heat-affected zone (HAZ) and the unaffected cold substrate when a clad cools after it re-solidifies, and/or (2) solid-state-phase-transformation induced volumetric change in the clad and the underneath HAZ of the substrate when the clad cools after it re-solidifies. In most cases, tensile residual stresses may arise in the clad, which cause potential cracking within the clad and/or the substrate, and adversely affect ultimate mechanical performance (such as fatigue strength or resistance to stress corrosion) and dimensional stability (i.e., distortion) of the base material being deposited. Even so, it could still be expected that this problem could be lessened or resolved by various approaches, such as optimizing processing parameters, creating an interlayer to minimize the thermal mismatch between the clad and the substrate, preheating the substrate during cladding, or performing post-cladding stress-relieving treatments, etc. [16,17].

To have a comprehensive understanding on the nature of residual stresses in the clad and their controllability will be beneficial to the development of laser cladding process and the improvement of in-service mechanical performance of the base material being deposited (here it is referred to the plastic injection molds made by P20 tool steel). The residual stresses, however, could not be measured directly, but only deduced from the measured strains by using elastic constants. Moreover, to quantify these stresses within a clad layer is not always straightforward. Generally, numerical simulation and modeling are popular approaches in predicting residual stresses in the clad layer [18–20], but those predictions require comprehensive knowledge of thermo-physical and thermo-mechanical properties of the materials and their evolution as a function of temperature, which are not always available to the investigators. Moreover, extensive experiments are still required to validate those theoretical predictions. Nevertheless, experimental studies of process-induced residual stresses are still the most adopted approaches in laser cladding [21–26]. Existing measurement techniques can be divided into mechanical stress relaxation methods (such as hole-drilling) and nondestructive methods (such as X-ray and neutron diffraction), which are based on the relationship between physical or crystallographic parameters and residual stresses [27]. The hole-drilling method can be used to determine average stress level in a clad layer, which measures relieved strains by the frozen residual stresses surrounding a hole being drilled on the surface of the clad, but the sensitivity of the measurement rapidly declines with increasing the depth of the hole. X-ray and neutron diffraction methods are based on the measurement of lattice strains by studying the variations in crystal lattice parameters of a polycrystalline material: the first method measures the residual strain on the near-surface of the material; and the second one measures the residual strain within a volume of the sample. Since X-ray diffraction technique is limited to sample the near-surface information, and mechanical/electrochemical layer removal is required to obtain the through-thickness information on the clad and substrate. By contrast, neutron diffraction can nondestructively obtain profiles of residual stresses across the clad and substrate. However, this method requires a special neutron source. Both hole-drilling and neutron diffraction have the capability to measure the residual stresses in a clad with the existence of certain degree of directionally solidified microstructure induced by laser cladding [28], while this type of preferred crystallographic orientation in the clad indeed arises some concerns during X-ray diffraction measurement using conventional $\sin^2\Psi$ method [29]. It is understood that an appropriate choice of adequate techniques depends on specimen related features and spatial resolution required for the measurements.

Table 1
Chemical compositions of AISI P20 tool steel powder and wrought substrate (wt.%).

Element	Powder	Substrate
Chromium	1.86	1.40–2.0
Molybdenum	0.53	0.30–0.55
Manganese	0.83	0.60–1.0
Silicon	0.67	0.20–0.80
Copper	0.02	
Carbon	0.40	0.28–0.4
Sulfur	0.01	
Phosphorus	0.01	
Iron	Remainder	Remainder

This paper presents an experimental study on process-induced residual stresses in laser clad AISI P20 tool steel onto pre-hardened wrought P20 base material (or substrate) and their correlation with microstructure evolution. Since the hole-drilling method (ASTM E837-95) is relatively accessible, only overall values of the residual stresses are provided in the clad; while the neutron diffraction can provide profiles of residual stresses across the clad and substrate, both methods were employed in the current comparative investigation. X-ray diffraction (XRD), scanning electron microscope (SEM) and microhardness tester were used to study the microstructures in the laser clad P20 tool steel. Combined with the above experimental analyses, the roles of solid-state phase transformations in the clad and HAZ of the substrate on the development and controllability of residual stresses in the clad have been discussed, and the results thus obtained could be used to effectively repair damaged plastic injection molds made by P20 tool steel.

2. Experimental

2.1. Cladding and substrate materials

The commercial Micro-Melt® P20 tool steel powder manufactured by Carpenter Powder Products Inc. (Bridgeville, PA) was used as cladding material. The powder was spherical in shape with a size range of 44–63 μm (−230/+325 mesh). Wrought AISI P20 tool steel plate with a thickness of about 10 mm, was used as a substrate for laser cladding. Prior to cladding, the base material was austenitized at 845 °C, and then quenched into the water and subsequently, tempered at 205 °C for 2 h. The surface of the P20 substrate was grounded and degreased with acetone in order to maintain a consistent absorption of laser beam during cladding. The chemical compositions of the P20 tool steel powder and substrate are listed in Table 1.

2.2. Laser cladding process and post-cladding stress-relieving treatments

The laser cladding process with injecting powder feedstock, illustrated in Fig. 1a, was used for the current study. The experimental setup employed a 3 kW continuous wave (CW) CO_2 laser (model: GE Fanuc C3000), a precision powder feeder (model: Mark

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