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The effects of solid-state phase transformation upon stress evolution in laser metal powder deposition

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ABSTRACT

To investigate the influences of solid-state phase transformation on stress evolution during multi-pass laser metal powder deposition (LMPD) process, a 3D finite-element (FE) thermo-mechanical model considering phase transformation has been established. The influences of phase transformation such as mechanical properties changes, volume change and transformation induced plasticity (TRIP) are taken into account. Furthermore, the influences of high magnitude stress upon martensitic transformation characteristic temperature and TRIP are considered. The temperature and history (microstructure) dependent material properties used in the present research are obtained by experiments. The stress field during LMPD process is analyzed with and without solid-state phase transformation, respectively. Stress measurement of X-ray diffraction (XRD) method is applied to deposited samples, and the measuring data are compared with the computational predictions. The results show that phase transformation has a dominant effect on the stress evolution, longitudinal residual stresses significantly reduced as a result of solid-state phase transformation. In addition, the effect of stresses on martensitic transformation temperature is important for accurate prediction of residual stresses (stress state after cooling of the clad to ambient temperature). Residual stresses are lower when the phase transformation temperature is reduced.

1. Introduction

Residual stress is one of the major issues affecting the large-scale commercial applications of laser metal powder deposition (LMPD). The complex thermal cycling of the process unavoidably relates to the evolution of stresses and strains and lead to cracks and distortion. Moreover, the magnitude and distribution of residual stresses may strongly influence the service behaviors, for example, the tensile residual stresses are often considered to reduce the strength of the material, induce stress corrosion and short the fatigue life [1–6]. Therefore, a valid approach to control the residual stresses is one of the most crucial problems to be solved in LMPD [7]. Using high-precision prediction calculation methods can assist in mitigating stress peaks and rearrange the stress distribution in favor of the product's usage.

Similar to ordinary welding process, the LMPD process parameters and material properties are the main factors affecting the evolution of stresses. With regard to some materials, phase transformation take place and greatly influence stress evolution during LMPD process. For example, the martensitic transformation in ferrous materials is often accompanied by the change of mechanical properties, volume growth and TRIP, etc., which will profoundly influence the development of residual stresses [8,9]. In order to improve the accuracy of predicting the residual weld stresses and strain, it has become the research focus for years to adopt the microstructure transformation effects into the weld thermal-mechanical simulation models [10–19].

Ghosh and Choi [10,11] have established a thermal-mechanical-microstructural model in which the effects of phase transformation are taken into account. It is found that stress evolution is sensitive to phase transformation. Phase transformation lead to the reduction of tensile stresses and even the emergence of compressive stresses. This model is very valuable. However, it can be improved because it is merely applied to single-pass welds, since it does not consider phase transformation induced by a new weld pass. Dean Deng et al. [13] have established a thermal-mechanical FE model. In his model, volume change as a result of martensitic transformation, mechanical properties variation due to microstructure change and TRIP have been take into account. It is concluded that the influence of phase transformation on welding residual stresses is important, the effect of TRIP should also be considered for accurate prediction of residual stresses. Lee and Chang [14,15] have developed a finite element model to predict the residual stresses of high carbon steel butt weld. The results show that phase transformation has significant effect on longitudinal tensile residual stresses due to volume change. In fact, many other valuable FE

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models considering phase transformation have been established by Ferro et al. [16], Wang and Felicelli [17], Shirish et al. [18], in the past few years. However, these models are similar as the model proposed by Ghosh and Choi, they do not consider phase transformation induced by the following weld pass.

A thermal-kinetic model has been presented by Costa et al. [19,20] to simulate temperature field and microstructure in parts of AISI 420 tool steel built by LMPD. The effect of solid-state phase transformation upon temperature field is considered. This model can be applied to multi-pass weld and LMPD process, since the solid-state phase transformations induced by the thermal cycles are considered when a new layer of material is deposited. However, this model does not address the stress problem. Borjesson and Lindgren [21] have developed a valuable FE model to predict the residual stresses of multi-pass butt welding. But this two dimensions model can be extended to three dimensions. Residual stresses have been calculated and measured by Becker et al. [22] for multi-pass girth welds including post-weld heat treatment. However, the physical processes and computational process are only briefly detailed.

In addition, the kinetic model of solid-state phase transformation and constitutive model considering phase transformation are the foundation for accurate prediction of stresses. The study of these nonlinear and strongly coupling problems continues to be a very active field [23–26], and further discussions on these subjects are essential. For example, the effects of stress on martensitic transformation are extremely complex, and the influence becomes significant under high magnitude stress [24,25]. TRIP increases very quickly when the tensile stresses exceed about a half of yield stress of high temperature phase. And it is well known that the magnitude of principal stresses is almost close to the yield strength of the clad material at certain temperature during LMPD process. As mentioned in the classical work by Francis et al. [27], however, the existing models of computational welding mechanics do not take into consider the nonlinearity of the TRIP versus the high magnitude stress. Moreover, the martensite starting and ending temperatures can be significantly influenced by high magnitude stress [28,29]. With regard to the material used in the present work, martensite start temperatue (M_s) can be increased by about 200 °C by stress comparable to the yield strength of austenite.

Based on the above discussions, although considerable progress has been made to predict the residual stresses during welding or LMPD process, there are much left to do.

In the present research, a FE model considering solid-state phase transformation has been developed to simulate the stress field during single-pass and multi-pass LMPD process. Not only the dependence of mechanical properties (yield strength) on phase volume fractions and temperature, but also the volume change and TRIP are taken into consideration. Furthermore, the influences of high magnitude stress upon TRIP and martensitic transformation characteristic temperatures are taken into account. The thermal and mechanical material parameters used in the present research are obtained by experiments. The stress fields of both single-pass and multi-pass LMPD process are predicted by the numerical simulation. The numerical results are validated by the experimental residual stress distributions of the XRD method.

2. Experiments and establishment of the FE model

2.1. Experiments

A 6-axis robot equipped with continuous wave IPG fiber laser (4 kW, wavelength 1070 nm) was employed to fabricate the sample. The laser beam energy density was uniformly distributed of which the wavelength was 1070 nm. The parameters used for the process were: power of 2000 W with a defocused laser spot of 3 mm, overlapping rate of 50%, speed of 10 mm/s and powder flow rate of 29.5 g/min. The alloy powder used in the present experiment was martensitic stainless steel with the nominal chemical composition of 16 wt.% Cr-4.5 wt.% Ni-1.6 wt.% Mo-0.9 wt.% B-0.6 wt.% Mn-0.12 wt.% C. The particle size range of the powders was 45–100 μm. The wrought FV520 (B) plates with the size of 6 mm × 40 mm × 60 mm were used as substrate. Three single-pass samples and three multi-pass samples (Two layers, eight passes) were fabricated for residual stress tests. Two large bulks with the size of about 135 mm × 65 mm × 27 mm were made for the property parameters tests.

XRD method was adopted for the residual stress measurement in which the XSTRESS3000 residual stress measuring instrument was used. Cobalt target was used in the present experiment. The residual stresses of the tested area were the average value of measurements. Specimens were cut from the large bulk to prepare for the property parameters tests. The high temperature properties with regard to material mechanics were obtained by an MTS810 mechanical testing machine according to the ASTME21-05 standard. Free dilatometric tests were carried out by DIL801 thermal expansion test instrument referring to Chinese National Standard of GB/T 4339–2008. The specific heat was obtained with Setaram Setsys Evo thermal analyzer according to the standard ASTME1269-11, while the thermal conductivity obtained with Netzsch LFA427 laser thermal conductivity meter according to the standard ASTME1461-11.

2.2. The process of solid-state phase transformation

Fig. 1 is the schematic of phase transformation for the martensite stainless steel during the LMPD process [19]. Austenite is assumed to be the initial phase during solidification process. Moreover, the martensitic transformation rather than diffusion phase transformation occur during the cooling process due to the high cooling rates. As temperature decreases, the martensitic transformation starts at M_s and finishes at M_f, the martensite start and martensite finish temperatures, respectively. The volume fractions of martensite (f_M) phase can be given by K-M equation [30]:

$$f_M = 1 - f_{\gamma_0}\Phi(T)$$
$$\Phi(T) = \begin{cases} 1, & T \geq M_s \\ \exp(-0.011 \cdot (M_s - T)), & T < M_s \end{cases} \quad (1)$$

in which f_{γ_0} is the initial austenitic volume percentage, and $f_{\gamma_0}\Phi(T)$ is the proportion of austenitic at a given temperature T.

When a new layer of material is deposited, the previously deposited material undergoes a new thermal cycle. Once the rising temperature is higher than Ac_1, the transformation of martensite to austenite takes place. It is presently assumed that the initial and final austenitic ratio is f'_{γ_0} and 100% when the temperature rise up to Ac_1 and Ac_3, respectively; the percentage of austenite phase increase linearly as temperature rise.

$$f_\gamma = f'_{\gamma_0} \cdot (T - Ac_1)/(Ac_3 - Ac_1) \quad (2)$$

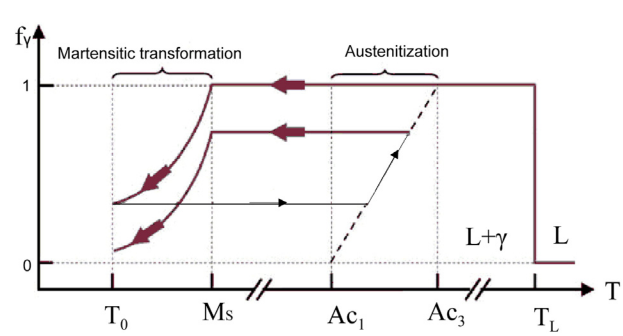

Fig. 1. Evolution of volume fraction of austenite during phase transformation.