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The role of metallurgical solid state phase transformations on the formation of residual stress in laser cladding and heating

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Abstract. There are two major types of solid state phase transformations in metallic materials; the formation of second phase particles during heat treatments, and the transformation of the matrix from one crystalline packing arrangement to another during either heating or cooling. These transformations change the spacing between adjacent atoms and can thus influence the residual stress levels formed. The heating and cooling cycles of materials processing operations using lasers such as cladding and melting/heating, can induce phase transformations depending on the character of the material being processed. This paper compares the effects of the different phase transformations and also the influence of the type of laser processing on the final residual stress formed. The comparisons are made between laser clad AA7075, laser clad Ti-6Al-4V and laser melted nickel-aluminium bronze using neutron diffraction and the contour method of measuring residual stress.

Introduction

Laser material processing is finding increasing application as a repair technology for components that have suffered foreign object damage, wear or corrosion [1, 2]. Often the components to be repaired are subjected to fatigue loadings and therefore an evaluation of the residual stress is required to satisfy regulatory bodies such as the Directorate General Technical Airworthiness (DGTA) in Australia. Each of the three repair technologies being develop by the Defence Materials Technology Centre (DMTC) have had the laser cladding and heating process components of the repair evaluated for residual stress using neutron diffraction and the contour method. The results of this work have shown that phase transformations have played a significant role in formation of the resultant stress state.

There are several types of phase transformations in metallic alloys including, liquid-solid transformation, the formation of second phase particles and displacive transformations such as martensite or bainite formation. For second phase particle formation alloying elements that are in solution combine to form precipitates. When in solution the alloying elements have an effect on the particle spacing depending on their atomic radius and electronic interactions with the main matrix element [3]. Then when precipitated, this changes the atomic packing and also the atomic spacing. If neutron diffraction is employed to measure residual stress this change in the atomic packing has an impact on the value derived for the residual stress and therefore needs to be considered. Displacive transformations, such as martensite or bainite formation [4], undergo both a shear displacement also known as an invariant plane strain which is accompanied by dilation normal to the invariant plane. The dilation component of the transformation that is responsible for exerting a compressive stress on the transformed region, can counteract existing tensile stress depending on the temperature range over which the transformation takes place [5].

This paper compares the results of several neutron diffraction and contour residual stress studies of different materials and analyses the results with respect to the different material properties and the type of phase transformation that occurred.

Experimental

The AA7075 clad layers were prepared using 2.5 kW fiber-delivered Nd:YAG laser. Residual stress measurements were then performed using neutron diffraction on the Kowari strain scanner at ANSTO. Details of the laser cladding and neutron diffraction measurements can be found in [6]. The Ti-6Al-4V clad layers were also laser clad with a 2.5 kW fiber-delivered Nd:YAG laser. Residual stress measurements were conducted using both neutron diffraction on the Kowari strain scanner ANSTO as well as the contour method, also performed at ANSTO. Details of the laser cladding and residual stress measurements can be found in [7, 8].

Laser processing of as-cast Nickel-Aluminum Bronze (NAB) with nominal composition Cu-8.5Al-5Ni-4.5Fe (wt.%) was carried out with a fiber coupled, 2.5 kW Rofin-Sinar Nd:YAG laser. The beam was delivered via a 1 mm diameter optic fiber terminated with a 200 mm collimating and focusing optic attached to an ANCAR CNC table. The surface of the NAB was grit blasted to increase absorption of the laser. Laser melting was conducted with a laser power of 1000 W with a Gaussian spot size of 3 mm diameter and a laser traversing speed of 1500 mm/min. Each track was 30 mm in length and an inter-track spacing of 0.5 mm was used to produce 30 mm^2 regions of melted material.

Residual strain through-sample-thickness scanning was carried out using the neutron diffractometer Kowari. The neutron beam had a wavelength range of 1.20-2.85 Å with peak intensity at 1.5 Å. The {311} lattice plane for copper was selected because it was found to have a peak at approximately $2\theta = 90^\circ$ and an adequately high intensity with which to conduct the experiment. Also in FCC crystals this reflection is well behaved when the macroscopic stress exceeds the yield stress, i.e. it is not especially prone to errors associated with intergranular strains. To determine the in-plane stresses and unstrained lattice parameter d0, the average d-spacing was calculated from 25 points measured in the x-direction and was repeated at 11 locations traversing in the y-direction with data collected in three perpendicular directions (two perpendicular in-plane directions and one normal). In order to calculate stresses from strains, Hooke's law was used with elastic constants E311 = 115 GPa and ν311 = 0.328 [9].

Residual stress measurements using the contour method first required the specimens to be sectioned using a wire electro discharge machine. The cut surface profiles were then measured on a Brown and Sharpe coordinate measuring machine equipped with a touch probe system. Each cut surface was measured with a 0.1 mm x 0.1 mm grid spacing. The residual stresses were calculated from the raw contour data using MATLAB scripts and ABAQUS Finite Element code.

Results and Discussion

Second phase precipitation transformation

AA7075 is a heat-treatable high-strength aluminium alloy that is used in the aerospace industry. The heat treatment or ageing process associated with the production of this alloy produces a fine precipitate state when in the T6 condition. When laser cladding is performed with this material as the substrate and clad layer, the particles experience heating and this changes the state of precipitation depending on the time and temperature that each region of the heat affected zone experiences. Fig. 1 shows the measurement of the lattice spacing as a function of position and reveals that there are significant changes in the lattice spacing, which can be attributed to the effect of the heat from the laser. Both zinc (Zn) and magnesium (Mg) increase the lattice parameter when in solution [3], however the measurement of the lattice spacing was conducted three months after the cladding therefore natural aging would have taken place. In the clad layer the lattice spacing is lower than that of the substrate and this can be attributed to the loss of Mg and Zn during processing [6]. However in the heat affected zone the initial precipitates would have been dissolved by the heat from the laser and then re-precipitated by natural aging. The fine precipitates that form are responsible for the increase of the lattice parameter just below the substrate. Beyond this region however, the thermal gradient in the substrate produces a slight coarsening of the existing precipitates as opposed to dissolution and as such the lattice spacing decreases [3].

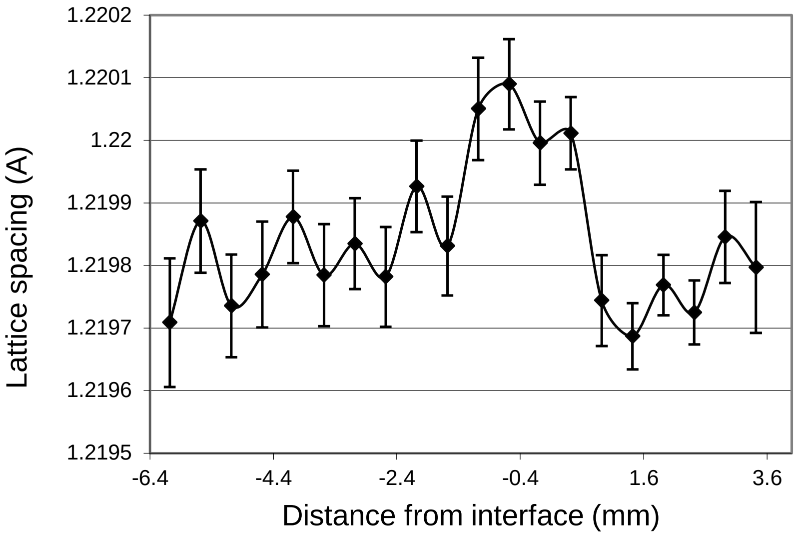


Fig. 1 – Lattice spacing as a function of position in clad and substrate position for laser clad AA7075 powder on a AA7075 substrate.

The effect of this changing precipitate structure on the residual stress developed is mainly in taking into account the effect of the changing lattice spacing as a function of position and hence the changing d0 as a function of position. It should be noted that as the solute levels change the yield strength of the metal will change as well, which will influence the stress levels formed as the residual stress often follows the yield envelope. However it has been shown that the natural ageing in 7xxx series aluminium alloys does reduce the residual stress in friction stir welds [10]. This phenomenon can be attributed to load sharing between the precipitates and the matrix. Essentially the precipitates are stiffer than the matrix and therefore sustain a higher fraction of the load [11]. The total fraction of the precipitates determine how much of the load is shared by the precipitates and given that the fraction of precipitates is relatively small in 7xxx aluminium alloys the effect is subtle.

Martensitic phase transformation

The calculated residual stress profiles for the laser melting of NAB and the laser clad Ti-6Al-4V on a Ti-6Al-4V substrate have been plotted on the same graph for comparison in Fig. 2, where a noticeable inflection can be seen at the interface between the laser processed region and the substrate. This inflection is characteristic of the transition between the region undergoing a martensitic transformation and the adjacent heat affect zone that does not undergo a phase transformation [12]. The transformed region experiences the dilation which lowers the residual stress whereas the adjacent region does not experience the transformation strains and as such forms a higher residual stress and therefore the residual stress profile exhibits an inflection.

Table 1 – Physical and Phase Transformation Properties

	Melting Point (°C)	Martensite Start (°C)	Martensite Finish (°C)	Elastic Modulus (GPa)	Thermal Expansion (µm/m/°C)
NAB	1035	500	150	115	16.2
Ti-6Al-4V	1604	994	575	113	8.6

The stress level at which the inflection occurs was found to be different for the two materials and can be attributed to a number of factors. As shown in Table1 the martensite finish temperature for Ti-6Al-4V is considerably higher when compared with NAB, the difference being 425°C. This temperature difference means that the Ti-6Al-4V has a greater cooling range to develope tensile residual stress following transformation when compared with NAB. The rate at which the tensile residual stresses develop is determined by the temperature differential, along with the thermal expansion cooefficient and elastic modulus. For both materials the elastic modulus is similar, Table 1, whereas the thermal expansion cooefficient of Ti-6Al-4V is almost half that of NAB. As a result, the rate at which the tensile stresses form in the NAB due to cooling will be higher, even though the Ti-6Al-4V cools futher after the martensitc tranformation. Therefore the difference in the residual stress levels at the inflection between the two materials is only 100 MPa, which is relatively small when considering they are both high strength materials. This work does highlight that a lower martensitic tranformation temperature is effective in reducing tensile residual stress levels and is consistent with the findings of [5, 13, 14].

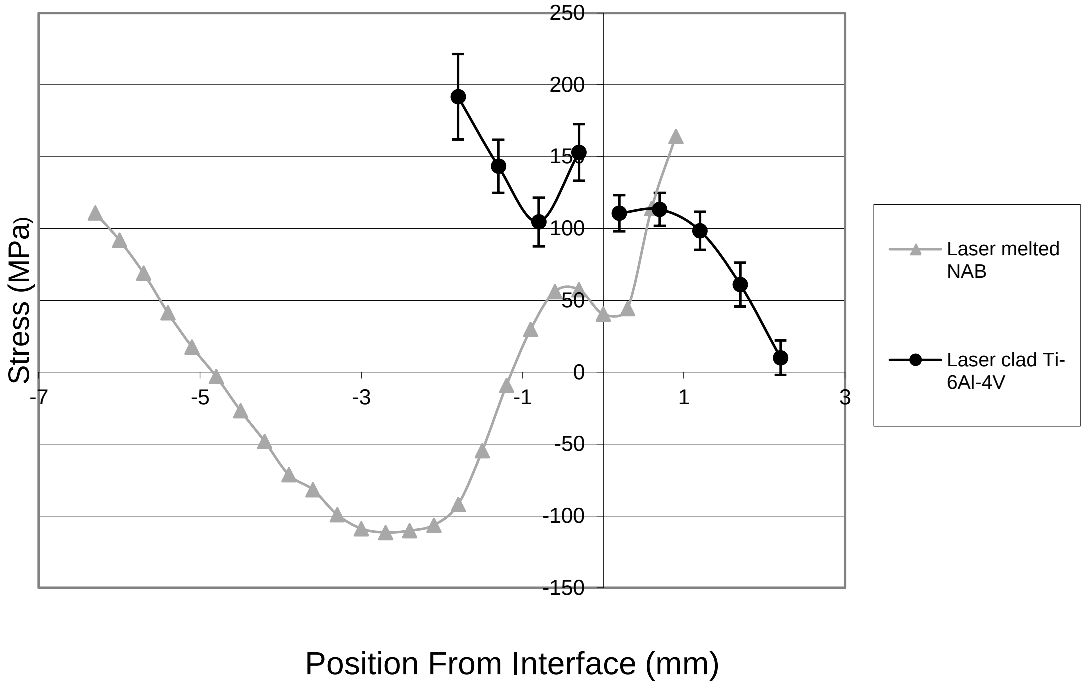
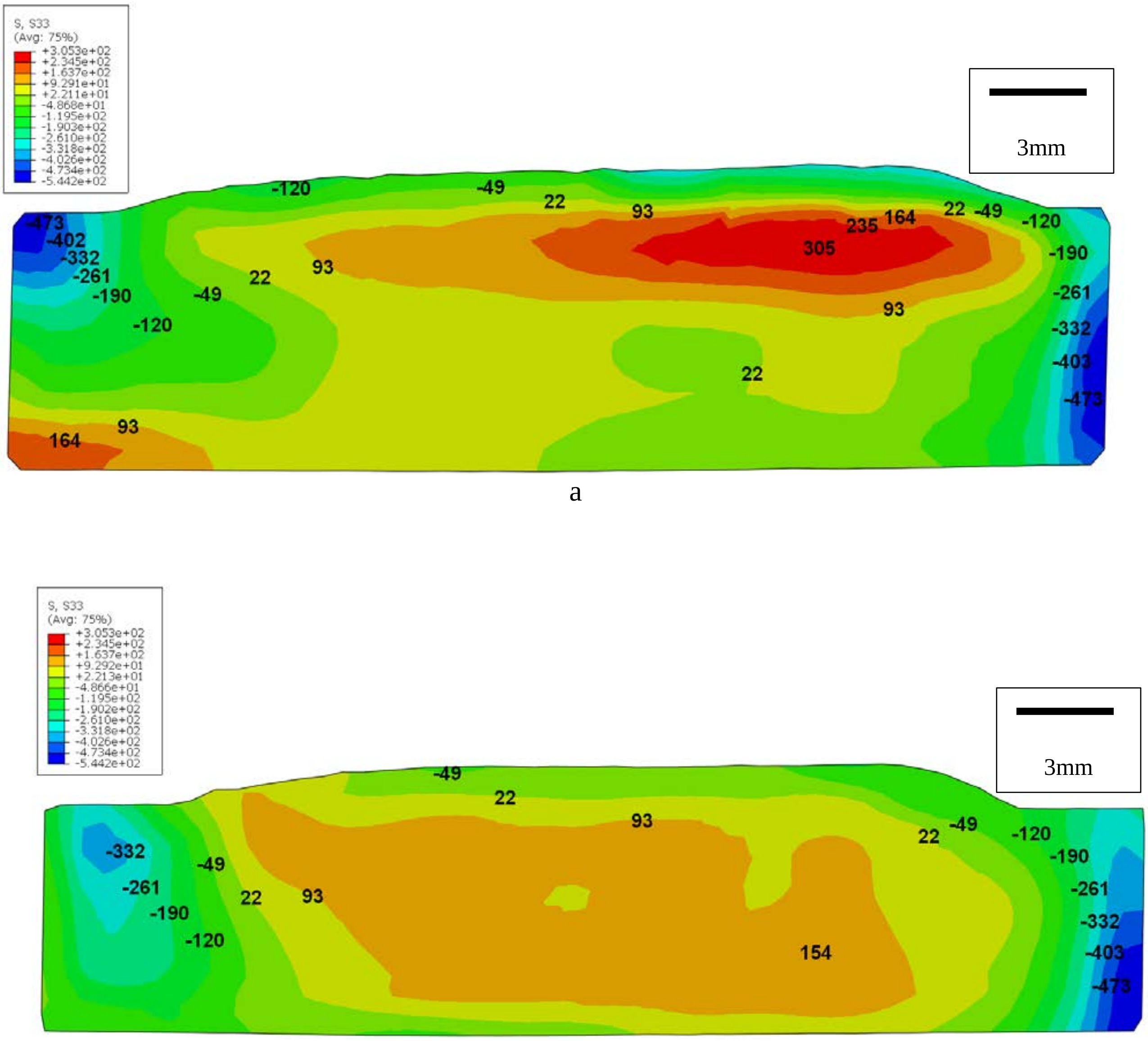


Fig. 2 – Residual stress profiles for laser melted nickel-aluminium bronze and laser clad Ti-6Al-4V on a Ti-6Al-4V substrate.

Fig. 3 shows that not only does the occurrence of a martensitic phase transformation influence the residual stress formed but the size of the transformed region also plays a role. The larger heat input of residual stress plot *b* in Fig.3 produces a deeper heat affected zone which in turn increases the volume of material that transforms and moves the peak stresses deeper in to the substrate. This increase in the amount of martensite that transforms has the effect of lowering the stress levels in the clad and heat affected zone when compared with stress plot *a*, where the stresses in these regions are considerably higher.



b

Fig. 3 – Contour residual stress profiles of Ti-6Al-4V clad on Ti-6Al-4V cut perpendicular to the clad track direction, where the numbers are the stress levels in MPa; a – laser power of 862 W with a traversing speed of 1500 mm/min; b – laser power of 1477 W traversing speed of 1500 mm/min.

Conclusions

Both types of solid state phase transformations analyzed in this paper have an influence on the measurement and final residual stress levels produced. The particle precipitation state of AA7075 in the clad and heat affected zone affects the d0 spacing and it has been noted that the precipitation process can reduce residual stress through load sharing. The effect of the martensite transformation is slightly more complex and acts to reduce the residual stress level in the transformed region. The inflection in the residual stress level just beyond the laser processing interface was attributed to point at which the martensitic transformation ceases resulting in an increase in the observed stress levels in the adjacent untransformed region. Finally it was shown that by manipulating the heat input and cooling used when cladding can increase the volume of transformed martensite to further reduces tensile residual stress levels and moves the location of the peak residual stress deeper into the substrate, which may be beneficial to the service life of a component.

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