CHALLENGES OF LASER CLADDING Al 7075 ALLOY WITH Al-12Si ALLOY POWDER

Y. Durandet, M. Brandt, Q. Liu

IRIS, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia
1 Defence Science and Technology Organisation (DSTO), Melbourne, Victoria 3207, Australia

ABSTRACT

Compared to conventional arc-welding processes commonly used to repair aluminium (Al) components, laser cladding involves lower overall heat input, less part distortion and narrow heat affected zones (HAZ). With the development of high power lasers, it has become an attractive technology for the refurbishment of high value-added structural airframe components in commercial and military aircrafts, especially those made of hard-to-weld heat treatable Al alloys. A series of cladding trials was performed on Al7075-T6 alloy substrates using an Al-12Si alloy powder as the filler repair material because of its high corrosion resistance and a high power Nd:YAG laser. The effects of laser operating parameters such as laser power, substrate scan rate, powder feed rate and increment between cladding tracks on the clad characteristics, e.g. height, depth and dilution, were investigated. Results are described, showing how the process conditions were optimized to reduce the clad depth, dilution and HAZ, while minimizing the formation of porosity in the clad during solidification. Clad samples were produced without liquation cracks in the HAZ, and despite the unavoidable formation of decorated grain boundaries near the fusion zone, the tensile strength of selected claddings was acceptable, within 5% of that of the parent metal, while ductility was low but similar to the parent metal.

1. INTRODUCTION

Laser cladding by powder injection is an advanced material processing technique used in metals manufacturing, including reclamation and repair of components, rapid prototyping and coating 1,2. During cladding, a jet of powder alloy is blown with the aid of a carrier gas into the melt pool formed by the laser on the surface of the substrate. Argon (Ar) is often used as the carrier gas that also shrouds the melt pool region and prevents oxidation. Particles arriving in the melt pool stick and melt instantaneously under the laser beam to form a clad layer. The level of mixing between the clad and substrate, usually called dilution, is indicative of the fusion bond at the interface. Dilution can be defined as the proportion of melted substrate relative to the whole melted volume and values of less than 10% are generally required.

The process is well developed for commercial applications to steel substrates as comprehensive studies have helped to map operating windows 3-5, particularly for the cladding of steel with cobalt-based Stellite alloy powder 6,7. Laser cladding of aerospace materials is however still the subject of much research and development 8. One application of interest is the repair of corroded areas in structural Al airframe components made of the heat treatable Al 7xxx alloy series using aluminium-silicon (AlSi) alloy powders, such as Al-12Si 9,10. Al-12Si alloy is an important filler metal with good casting characteristics, lower strength but very good corrosion resistance. One common way of repairing Al components is by inert gas arc welding, but the Al 7xxx alloys are normally considered un-weldable and are therefore good candidates for repair by laser cladding. The process involves lower overall heat input, less part distortion and narrow HAZ in the parent metal. Laser processing of Al alloys has however its own challenges. Compared to steel, Al alloys are highly reflective throughout the visible and infra-red range, so coupling the laser energy into the surface is more difficult 11, even more so when the time scale for energy absorption at the surface is short as Al alloys are good heat conductors. Nevertheless, this has partly been overcome since the 1990s with the development of high power Nd:YAG and diode lasers which can deliver laser beams with high energy densities at shorter laser wavelengths that yield greater absorption by Al and other metals than CO2 laser radiation 12. For laser cladding of Al alloys by powder injection, energy coupling can also be improved through the design of the powder delivery method and by adjusting the process parameters such as laser power, laser beam spot size, powder feed rate, scan rate or shielding gas 13.

More importantly, the high thermal diffusivity of Al alloys makes it equally challenging to reduce both the dilution and HAZ to retain the properties of both clad and substrate respectively. The substrate temperature generally rises during laser cladding and can lead to excessive dilution, softening, decorated grain boundaries or liquation micro-cracks in the HAZ 12,14,15, thermal distortion or cracking due to the build-up of residual stresses. This may occur with small components or heat sensitive substrates such as Al 7xxx alloys, and even large components if extended area coverage is required. For example, even with the use of a water-cooled chill block to remove heat from the substrates, the ultimate tensile strength of Al alloy clad joints produced with a Nd:YAG laser was reported to be 61% of the parent 7075-T651 substrate metal,
while corrosion testing showed some attack in the HAZ outside the fusion zone after twenty days of immersion in artificial seawater. Published micrographs revealed extensive dilution of the claddings suggesting that further optimization of the cladding conditions was needed. One added complication is the formation of porosity in AlSi alloy claddings due to the release of hydrogen during solidification as the solubility of hydrogen in molten Al is higher than in the solid. Sources of hydrogen may be from inadequate gas shielding, or moisture pickup during processing due to insufficient drying of the clad powder, or inadequate cleaning of the substrate. In previous studies where there was no forced cooling of the Al substrates and shielding of the melt pool was provided by the powder carrier gas only, porosity in Al-12Si claddings from undried powder was significantly reduced by reducing the laser power or powder feed rate, and increasing the scan rate. When the powder was dried, porosity was eliminated with increasing step increment between overlapping tracks, as well as scan rate. These conditions produced however thinner claddings with higher dilution as the powder feed rate was kept constant.

This paper presents the results of laser cladding experiments conducted on cooled Al7075-T6 alloy substrates using an Al-12Si alloy powder. Results are described to show the effects of processing conditions on the clad characteristics such as height and depth. Some mechanical test data are also presented for selected cladding parameters.

2. EXPERIMENTAL PROCEDURES

Continuous wave laser cladding was carried out using a 2.5kW Nd:YAG laser equipped with a 0.6mm diameter step-index optical glass fibre terminated with collimating and focussing lenses of 200mm focal length positioned to produce a laser spot size of 2 to 4mm diameter on the substrate’s surface. The melt pool temperature was measured by a Maurer KTR 1075 model two-colour optical pyrometer set up vertically above the substrate and at 90° to the collimating lens via a bending cube, as shown in Figure 1.

The substrates’ material was Al 7075-T6 plate of 6.25mm thickness. The plates were either plain flat, or with a machined groove of 0.6mm depth by 10mm width to simulate the repair cladding of corroded areas. The substrates were cleaned with acetone to remove any rolling lubricant or cutting fluid and fixed via two steel clamps onto a water-cooled copper chill plate. A Sulzer Metco S10 model powder feeder was used whereby the Al-12Si alloy powder was contained in a hopper with a spindle at its base to spin-deliver the powder at controlled mass flow rates. To dry the powder, a heating tape was wrapped around the base of the hopper and set to 100°C. Argon was used as both carrier and shrouding gas at a flow rate of up to 3L/min. The powder was blown into the melt pool via a side injection nozzle positioned at about 30° from normal and in-line with the scanning direction in order to minimize edge shadowing effects when cladding the grooved substrates, as shown in Figure 2.

Experimental parameters were the laser power P, varied from 1.5 to 2.2kW; the powder feed rate g from 0.07 to 0.15g/s; the traverse speed of the substrate V from 16 to 30mm/s; and the cladding step S from 0.8 to 1.3mm. The effects of these parameters on clad height, clad depth, clad thickness and dilution were investigated.

The average cladding’s characteristics were calculated from measurements of clad width (w) and of areas taken above (A₁) and below (A₂) the substrate’s original surface, as shown in Figure 3.

Measurements were made using quantitative light optical microscopy on transverse cross-sections
prepared following standard metallographic techniques. Where required, samples were etched using Keller’s reagent. Mechanical testing of selected samples involved micro-hardness measurements using a load of 100g applied for 15s, and tensile tests with the loading axis parallel to both the cladding and the plate rolling directions, performed at 0.4mm/min testing speed with a 25mm gauge extensometer.

3. RESULTS AND DISCUSSION

3.1 Claddings Characteristics

As shown in Figs. 4 and 5, the clad height increased with decreasing cladding step and scan rate, and with increasing powder feed rate and laser power.

![Graph showing the effects of powder feed rate, scan rate, and cladding step on measured clad height at 2kW laser power.](image)

Figure 4: Effects of powder feed rate, scan rate, and cladding step on measured clad height at 2kW laser power.

The combined effects of these parameters can be understood from a mass balance between the powder injection nozzle and clad layer as follows,

\[ \eta_p \cdot \dot{g} = \rho_c \cdot V \cdot S \cdot H \]  

(1)

where \( \eta_p \) is the powder efficiency, \( \dot{g} \) the powder feed rate in g/s, \( \rho_c \) the clad density, \( V \) the scan rate in mm/s, \( S \) the cladding step in mm, and \( H \) the clad height in mm. From equation (1), it can be seen that the clad height is proportional to the powder efficiency and powder feed rate and inversely proportional to the product \( V \cdot S \), or coverage rate \( R \) in mm²/s. By defining the nominal coating mass \( G \) in g/mm² as

\[ G = \frac{\dot{g}}{R} \]  

(2)

experimental results show that the measured clad height increased with increasing coating mass while the powder efficiency increased with laser power (Figure 6). Similarly, by defining the nominal energy input per unit area scanned during cladding \( E \) in J/mm² as

\[ E = \frac{P}{R} \]  

(5)

where \( P \) is the nominal laser power in W, it was found that the measured clad thickness, i.e. the thickness of the total melted volume, increased with increasing area energy while the melting efficiency increased with powder feed rate (Figure 7). However, at higher area energy and powder feed rate, claddings contained some porosity (Figure 8). Porosity trapped between successive overlapping passes indicates that the clad height was too large compared to the size of the melt pool, so there wasn’t enough energy absorption to melt the surface of the previous track.

Claddings also displayed a rough and porous surface layer that appeared to be shifted towards one side (left in Figure 8), suggesting some misalignment of the powder stream relative to the laser-generated melt pool. This porous crust formed due to the nozzle setup relative to the laser beam and scan direction (Figure 2)
that resulted in the powder stream to alternatively "lead" and "follow" the laser beam. Hence, periodic step-changes in clad depth (arrowed in Figure 8) and melt pool temperature (Figure 9) occurred with changes in the scan direction. When the laser beam was leading, the trailing powder absorbed less energy, so the melt pool temperature increased along the traverse length and caused more melting in the substrate. The high temperature values and noise in the temperature data probably resulted from back reflection of the laser wavelength to the pyrometer and light scattering by the powder stream. Nevertheless, the average melt pool temperature was found to increase with coating mass (Figure 10a) and area energy (Figure 10b), hence the total melted volume or clad thickness, clad height and clad depth increased with the melt temperature (Figure 11a).

Results so far were obtained with a laser spot size of 4mm and powder nozzle diameter of 2mm. By changing the powder nozzle diameter to 1.5mm, the powder melting efficiency was improved and further reduction in clad depth was achieved (Figure 11b). These effects may be related to the influence of the melt temperature on the melt pool size. Complex laser-powder-substrate interactions occur, associated with non-linear coupling of heat and mass transfer phenomena that affect the actual size and shape of the melt pool relative to the beam size.

Figure 8: Claddings produced at high area energy corresponding to conditions A, B, C and D in Figure 7.

Figure 9: Variations in melt pool temperature during a cladding run ($G = 5.3 \times 10^3$ g/mm², $E = 110.3$ J/mm²).

Figure 10: Influence of (a) the coating mass and (b) the area energy on the average melt pool temperature.

Figure 11: Influence of melt pool temperature (a) and powder nozzle diameter (b) on clad height and depth.
3.2 Properties

A set of laser cladding parameters was selected to produce claddings thick enough to fill in a single layer a 0.6mm deep groove. For those conditions, micro-hardness profiles showed that cooling of the substrates effectively minimized the depth of HAZ to about 1mm (Figure 12). The fine dendritic solidification structure of the clad (Figure 13a) yielded a hardness of HV103±6, while the substrate's hardness varied from about HV147±9 in the HAZ to HV154±11 in the parent metal. No liquation cracks were observed in the clad-substrate interfacial region, but the formation of decorated grain boundaries near the fusion zone, described previously 14, was unavoidable (Figure 13b).

As the claddings constituted not more than 10% of the cross-sectional area, properties of selected samples were overall comparable to the parent metal (Figure 14). The ductility of the clad plates was low, but similar to the parent metal. The tensile strength of clad grooved plates was 5% lower than parent metal, while that of clad flat plates was 1.5% and 0.5% lower for samples produced with a 2mm and 1.5mm diameter nozzle respectively. Fracture surfaces revealed some delamination at the clad-substrate interface (Figure 15a). Inter-dendritic failure occurred within the fine grain structure of the fusion zone (Figure 15b) in contrast to the mixed fracture mode in the substrate where relatively large insoluble iron-based second-phase particles fractured by cleavage (arrowed in Figure 15c), while limited plastic deformation took place in the surrounding matrix, as suggested by the presence of fine dimples.

Figure 12: Micro-hardness profile of selected clad sample 123 days after cladding with a 2mm nozzle.

Figure 13: Microstructure of (a) clad and (b) clad-substrate interface.

Figure 14: Tensile properties of selected samples 89 to 126 days after cladding.
4. SUMMARY AND CONCLUSIONS

The conditions to produce Al-12%Si claddings thick enough to fill in a single layer a 0.6mm deep groove machined in 6mm thick Al7075-T6 plates were investigated. The inter-related effects of laser power, scan rate, powder feed rate and track increment on clad height and depth were demonstrated through their influence on melt pool temperature via the use of coating mass and area energy variables. Operating parameters were determined to produce thick enough claddings with little or no porosity. The tensile properties of samples produced under those conditions compared well with the parent metal. Further optimisation can however be achieved with improvements in the powder nozzle design and alignment relative to the laser beam, especially to produce thicker claddings with shallower and more uniform clad depth for the repair filling of deeper grooves. While it appears that clad samples with adequate strength can be produced, their corrosion performance remains to be assessed. This will be the subject of further work.

ACKNOWLEDGEMENTS

The authors wish to thank the Cooperative Research Centre for Welded Structures, Australia, for the financial support under project No. 2000-312.

REFERENCES


