MICROSTRUCTURE AND MECHANICAL PROPERTIES OF LASER CLADDING REPAIR OF AISI 4340 STEEL

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Abstract

Laser cladding (LC) was used to investigate the repair of high strength steel in aircraft applications, such as landing gears. This paper reports on the microstructure and microhardness properties of the deposited AISI 4340 clad layer on AISI 4340 steel substrate. Microhardness results showed the clad layer was 30-40% harder than the base material. Stress relieving the clad allowed the clad and HAZ areas to soften 10% below the base material. High dilution provided a favorable result on the hardness at the interface.

1 Introduction

High strength steels such as AISI 4340 are used widely in aircraft, particularly in critical applications such as landing gear. However they are known to be vulnerable to corrosion, impact and they are fracture-sensitive [1]. In aerospace applications such as critical carry-through structures, discovering even a small crack will lead to the reduction in airworthiness, and it is therefore vital to repair even small damage features, or replace the component. A repair by grinding out the damage may exceed dimensional limits, and where this happens, and in order for the aircraft to remain in service, it is usual to replace the damaged component. As the cost of replacing the component can be high, potential methods for repair by rebuilding the damaged area and restoring strength are of interest.

A potential repair technology is laser cladding. The concept is to melt a metal powder, with appropriate mechanical properties, using a laser beam, to form a track of solid metal fused with the substrate material to form a metallurgical bond [2]. There has been great interest in using laser cladding as a repair method for aerospace applications [3, 4].

Several researchers have reported on laser cladding of high strength steel. Bhattacharya et al. [5] has reported on the microstructural features of laser clad AISI 4340 steel powder on mild steel substrate powder on substrate. Other research on AISI 4340 steel has involved in laser melting application [6, 7]. Fastow et al. [6] analysed the microstructural and microhardness evolution of AISI 4340 steel when laser melted using a 1.2kW CO_2 laser. McDaniels et al. [7] showed that the HAZ of a laser melted AISI 4340 steel did not have an adverse effect on the fatigue properties.

However, very little research has been published on the repair of laser cladding of aero-grade high strength steel. This paper focuses on the mechanical properties of laser cladding of AISI 4340 steel powder on AISI 4340 aero-grade steel substrate. Microstructural features and microhardness properties are analysed. The aim is to; (i) Identify microhardness and microstructure evolution of high strength steel. (ii) Effect of the laser processing parameters on the microhardness and microstructure.

2 Experimental details

2.1 Material preparation

AISI 4340 steel plates of dimension 180 mm x 100 mm x 6 mm (composition shown in Table. 1) were supplied in annealed condition The plates were then heat-treated, in accordance with ASM handbook [8], by quench hardening and tempering to achieve a representative in-service UTS level of 1400MPa.

Table. 1. Chemical compositions (in wt. %) of the AISI 4340 base material as provided by supplier.

C	Mn	Ni	Cr	Si	Mo	V	Fe
0.41	0.7	1.74	0.77	0.24	0.25	0.046	Bal

AISI 4340 powder was supplied by Sandvik Osprey Ltd. in the form of gas atomized spherical particles (-106+45µm).

2.2 Laser cladding

A 4kW IPG Photonics fibre laser with a co-axial powder delivery head was used to deposit each clad. A mixture of helium and argon was used as both the carrier and shielding gas. The shielding gas flow was 15L/min. A 16.0mm standoff height (distance between the tip of the cladding head and the melt pool) was used. The cladding head was tilted 5° relative to the melt pool in order to minimize any back reflections from the melt pool damaging the laser.

Each plate was cladded in the direction of rolling. A 5.0mm bead width and a 2.5mm overlap were used to clad. The approximate track length was 23mm.

2.3 Metallurgical procedure

Samples were cross-sectioned, mounted, polished to 1.0µm finish and etched with a 4% Nital solution, in accordance with standard metallographic procedures [9]. Microscopic examination was conducted using a Leica MEF3 optical microscope.

Microhardness measurements were performed using a LECO LM700AT micro-hardness tester. An applied load of 300gf was held for 15 seconds, in accordance with standard ASTM procedure [10].

2.4 Experiment design

A total of three design conditions were used for the analysis of microstructure and micro-hardness: (i) Baseline (ii) clad layer with 2 different laser processing parameters (iii) post heat treatment (PHT).

The laser processing parameters used for repair are those that produce defect free clad layer. Any clad defects such as porosity and micro-cracking could act as damaging stress concentrators and degrade the mechanical properties of the material. Two laser processing parameters are tested (Table. 2).

Table. 2. Laser processing parameters used for this research.

No.	Powder flow rate (g/min)	Laser speed (mm/min)	Laser power (kW)	Laser beam diameter (mm)
1	25	1400	4	5
2	20	800	4	5

The laser processing parameters were determined from initial trials of AISI 4340 steel cladding [11]. Since the aim was to determine the optimum clad, no grind-out area was employed in the initial trials. In Fig. 1a, the clad/HAZ fusion line is where the red region contacts the green region and dilution/HAZ fusion line is where the yellow region contacts the green region. The inconsistent dilution is due to the Gaussian laser intensity distribution, causing a higher temperature in the center of the clad track, where most of the energy is supplied [12]. Parameter 1 is a low dilution clad (Fig. 1b) and parameter 2 is a high dilution clad (Fig. 1c). Dilution (D) is the percentage of area that has melted into the base material (Eq. 1).

$$D = \frac{A_D}{A_C + C_D} \cdot 100 \qquad (1)$$

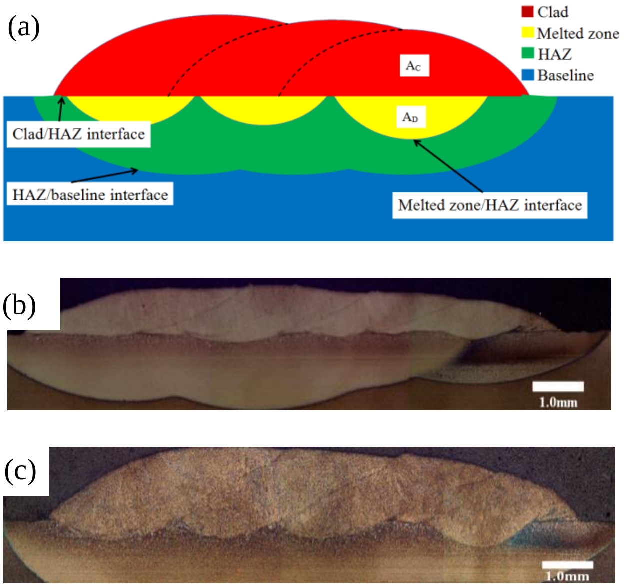

Fig. 1. (a) Schematic of a cross-sectioned multi-track clad (without grind-out) showing the 4 composite layers in a laser cladding process. (b) Clad 1. (c) Clad 2.

It is often reported when laser cladding to keep dilution to a minimum to minimize the mixing between the clad layer and the substrate in order to maintain the properties of the baseline material [13]. However, high dilution allows stronger bonding between the clad and base material and in some case may have beneficial properties [14]. It is known that in laser cladding the weakest point is the clad/HAZ interface due to inconsistent dilution/fusion [7, 15]. This research examines the effect of dilution on the hardness and static strength properties.

Residual stress and hardness variation occur in laser cladding due to high thermal gradients inherent in the process [16]. Residual stresses in clad material could affect the component's resistance to corrosion and fatigue cracks due to high thermal stress concentration. Post heat treating reduces the generated stresses at the clad/substrate interface and improves its mechanical properties. Post heat treatment was performed in accordance with ASM handbook standard [17] The process involved heating the clad plates to 560°C, and soaking for 3 hours followed by slow cooling to 250°C over 5 hours, and finally air cooling.

3 Results & discussion

3.1 Microstructure properties

3.1.1 Microstructure of the clad

For low alloy steel, the solidification structure consists of austenite dendrites and depending on the cooling rate, various other phases. The formation of a clad is dependent in part on the heating time which is influenced by the laser scan speed and is usually between 0.1-2 seconds [18]. The cooling rates of laser cladding are rapid usually between 10^3-10^6 k/s [19, 20]. For such high cooling rates with AISI 4340 steel material it is expected that the martensite structure to dominate the clad. Bhattacharya et al. [5] identified ferrite, martensite, and cementite phases in the microstructure of an AISI 4340 steel clad. Fastow et al. [6] showed that decreasing dilution generally results in a finer microstructure.

Fig. 2 shows that the clad layer consists of austenitic dendrites (white lines) where the growth is in the direction of solidification. Two distinct dendrite structures appeared in one single track clad; (i) cellular (Fig. 2a) and (ii) columnar (Fig. 2b). Dendritic formation is dependent on the heating and cooling rates. Heating and cooling rates are much more rapid near the surface [21] and temperature gradients generally exist across the solidifying structure resulting in the formation of different dendrites. A fine martensitic phase appeared within the dendrites due to rapid cooling rates. The black needles are constituents of bainite.

The dilution zone is a mixture of melted base material and clad powder. Since the powder and base material have similar chemical composition, the dilution zone has similar microstructural features to the clad zone.

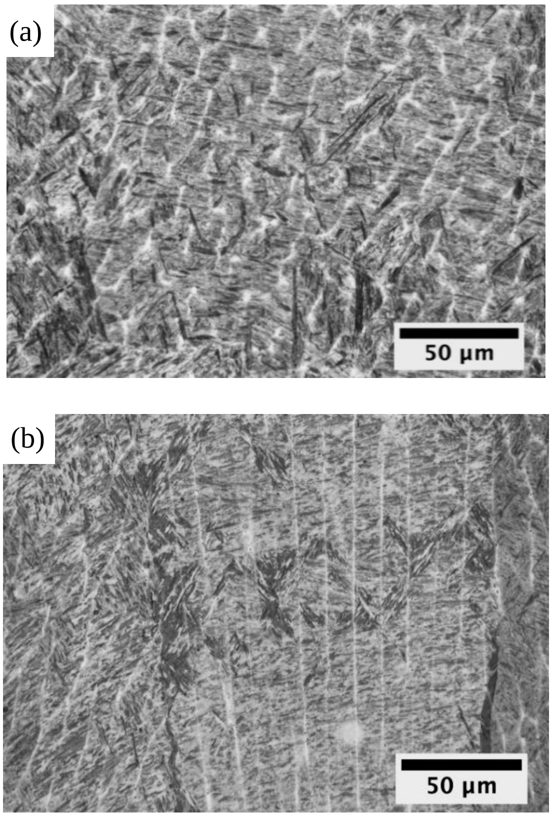

Fig. 2. Clad 2 parameters-20g/min, 800mm/min, 4kW (a) clad zone showing dendritic cellular structure (white lines) martensite (light grey areas between the dendrites) and bainite (dark needles) (b) clad zone with dendritic columnar structure.

3.1.2 Microstructure of the Heat Affected Zone

The HAZ is a complex heat treated area subjected to rapid heating with a short interaction time, followed by air cooling at room temperature during each pass. The heat treatment is similar to rapid quenching in air but using a range of heating temperatures. The HAZ starts from the clad/HAZ interface (Fig. 1a) where the peak temperature is just below the melting temperature of 0.4wt%C steel which is 1500°C (A_M) [22]. The temperature decreases proportionally to the HAZ depth, where according to the iron-carbon phase transformation diagram (Fig. 3), for a 0.4wt%C steel, the material will undergo γ and α phase transformation (γ at 800°C-1500°C, γ + α at 727°C-800°C) until the HAZ reaches the HAZ/baseline interface (Fig. 1a), where the cooling temperature reaches below the eutectoid temperature 727°C (A_1) which is the minimum temperature for γ transformation. Depending on the cooling rate, a variety of constituents may form such as martensite and bainite.

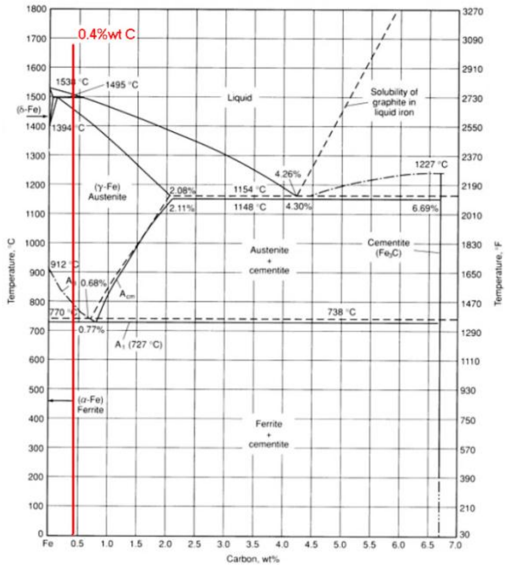

Fig. 3. Iron carbon transformation diagram. Red line indicates the phase transformations for AISI 4340 steel [23].

Directly below the clad/HAZ interface, where the peak temperature is just below A_M, the microstructure transformed to a coarser γ and upon cooling, transformed to an acicular ferrite (white needles) and lath martensitic/bainite structure (grey/dark regions), as shown in Fig. 4a. The martensite that formed is generally brittle due to the rapid cooling rate in air, and as a result, exhibits low ductility and toughness [8]. The coarsening of the γ grains near the clad/HAZ fusion line is due to high peak temperatures and causing high kinetic movement of atoms just adjacent to the clad/HAZ fusion line [24]. The coarsened HAZ caused significant grain growth, and as a result, the constituents of ferrite transformed into a more acicular appearance. The coarsening near the clad/HAZ interface is observed in welding [24] and other laser material processing where high heating temperature is applied [6]. Further away from the clad/HAZ interface, the grain size becomes finer due to decreased temperatures, and a traditional microstructure of a rapid quench heat treatment is observed (Fig. 4b).

The HAZ/baseline interface is distinctly identified (Fig. 4c), since transformation ceases when the temperature falls below A_1, where austenite transformation stops. The dark region is a microstructure of the baseline AISI 4340 steel prior to cladding. The white appearance in Fig. 4a is due to α constituent, where the heating temperature is just above A_1, consisting of γ + α transformation.

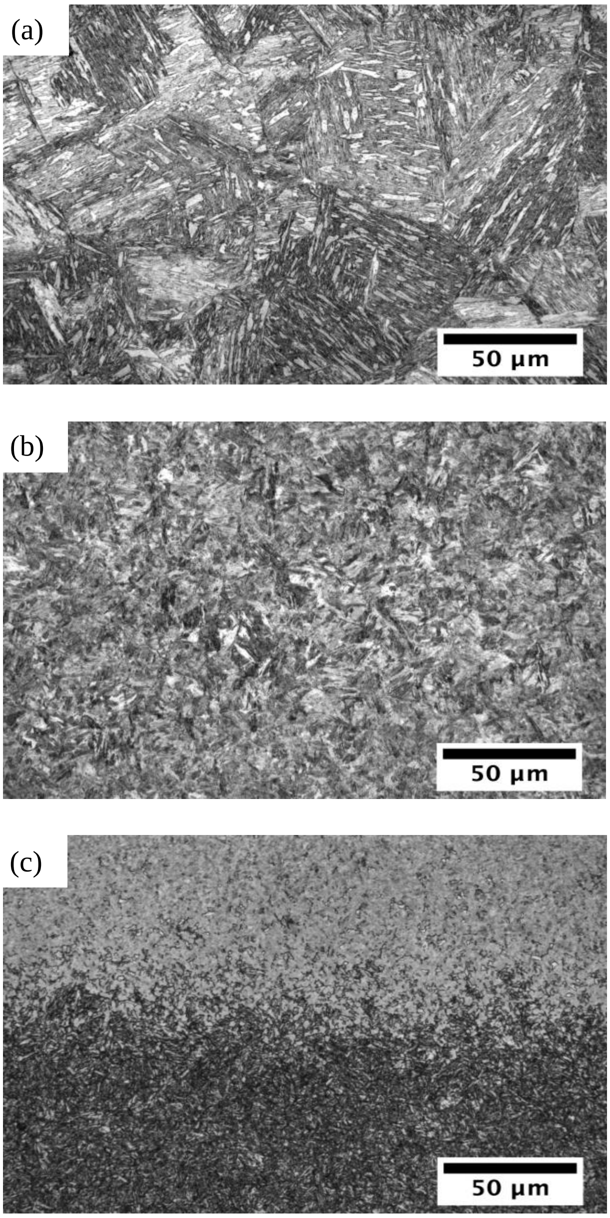

Fig. 4. Clad 2 parameters-20g/min, 800mm/min, 4kW. Microstructure evolution of the HAZ. (a) 0.2mm below the clad/HAZ interface. (b) 0.6mm below the clad/HAZ nterface. (c) HAZ/baseline interface.

3.1.3 Microstructure of Post Heat Treated (PHT) sample

The microstructure of the PHT clad and HAZ consisted mainly of α constituent, which is expected since the heating temperature of 560°C causes α transformation (Fig. 5). The acicular appearance of the ferrite is due to the longer heating time of the PHT procedure. The HAZ still maintained the coarsened γ grains near the clad/HAZ fusion line, as shown in Fig. 5b-c, which is expected since no γ transformation occurs in tempering.

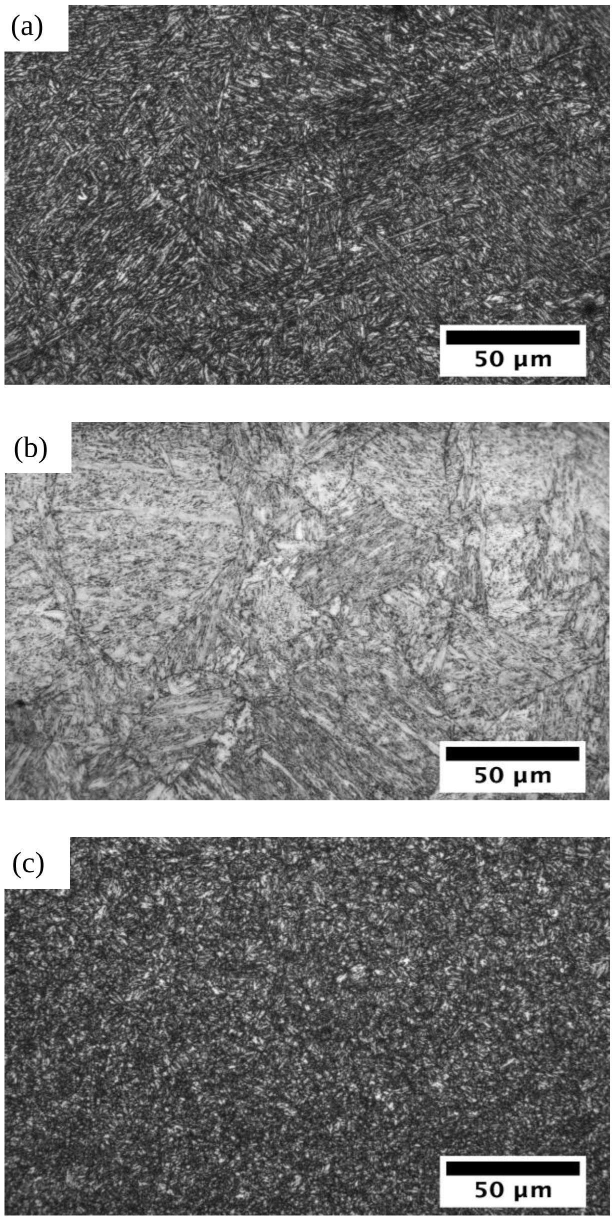

Fig. 5. Clad 2 parameters-20g/min, 800mm/min, 4kW. Microstructure of PHT of AISI 4340 steel (a) clad (b) 0.2mm below the clad/HAZ

interface (c) 0.6mm below the clad/HAZ interface.

3.2 Microhardness properties

3.2.1 General microhardness

Fig. 6 shows that the hardness of the clad was 30-40% higher than the base material. The high hardness in the clad was associated with martensite formed during rapid cooling of the melt pool (Fig. 2a). The average hardness of the dilution zone was similar to the clad.

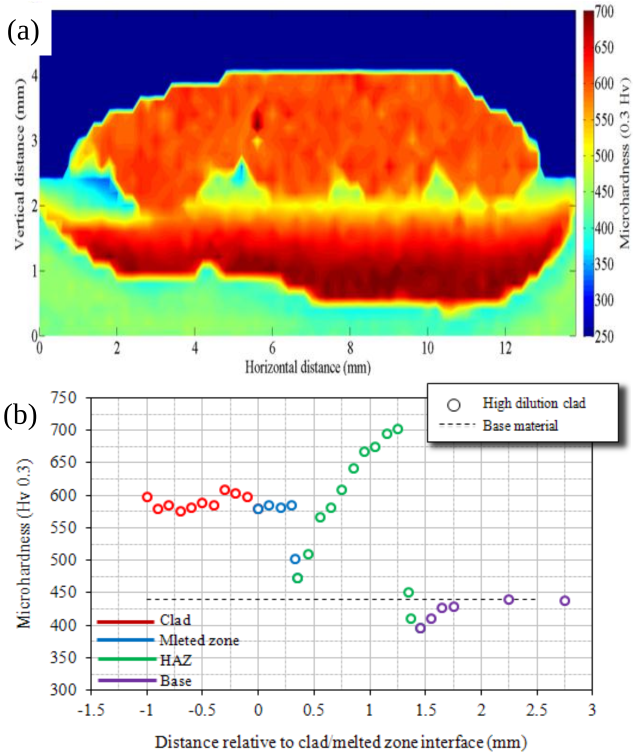

Fig. 6. (a) Microhardness contour plot of a multi-track clad area. Each indent was spaced out by 200µm. (b) Vertical microhardness profile, measured relative from the clad/melted zone interface (20g/min, 800mm/min, 4kW).

The hardness of the HAZ significantly increases almost linearly from the clad/HAZ interface to the HAZ/baseline interface, from 460Hv to 700Hv respectively, as shown in the green region in Fig. 6. The linear increase of the hardness in the HAZ is due to the heating temperature gradient in the HAZ causing a difference in grain growth. As discussed in section 3.1.2, a coarser microstructure is produced near the clad/HAZ interface due to high peak temperatures. The microstructure becomes finer away from the clad/HAZ nterface due to decreasing heating temperatures. A finer grain size is generally harder than a coarse grain size (Petch-Hall grain size effect [25, 26]). A similar microhardness trend in the HAZ was observed in laser melting of AISI 4340 steel [7].

The HAZ linearly increases to a maximum hardness of 700Hv, which is a similar hardness produced during a normal rapid quench hardening heat treatment process, where the heating temperature is between 815°C to 870°C [8]. Eventually the temperature reaches A_1 and hence no γ transformation occurs. As a result, at the end of the HAZ, a sharp drop in hardness occurs to near substrate conditions (380Hv). However, the hardness at the end of the HAZ is still 60Hv softer than the hardness of the substrate material. The softening is due to partial stress relieving/tempering which occurs just below the HAZ. The temperature just below the HAZ experiences similar heating temperatures for stress relieving of low alloy steel which is approximately between 595°C to 675°C [17] causing α transformation and softening the base material. The stress relieving effect fades after 0.5mm below the HAZ and the properties return to substrate condition.

3.2.2 The effect of dilution on microhardness

Fig. 7 showed that, for the low dilution (D=10%), the average clad hardness was approximately 650Hv. For a high dilution (D=30%), the average clad hardness was approximately 580Hv. D was calculated from Eq.1. The decrease of clad hardness with increasing dilution is due to the slower cooling rates at higher dilution. Dilution is a complex function of laser power, process speed and powder mass flow rate. Dilution increases with decreasing laser speed, increasing power, and decreasing powder flow rate [11]. Increased dilution means higher and concentrated melt temperatures due to longer laser interaction time, resulting in higher heating and slower cooling rates of the clad. The faster the laser speed is, the faster the cooling rate [27]. The hardness of steel decreases with longer cooling rate due to the decrease in martensite.

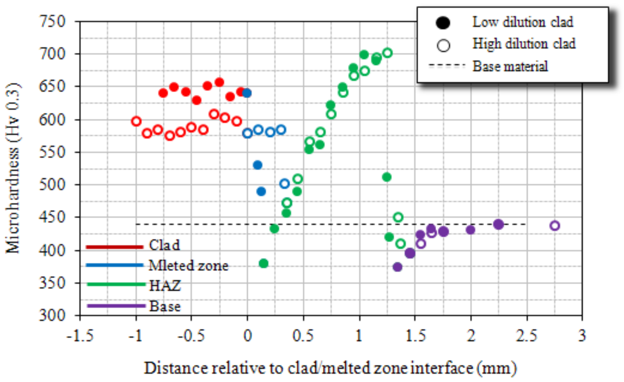

Fig. 7. Vertical microhardness profile, measured relative from the clad/melted zone interface showing the effect of dilution.

Other researches have also reported a variation of microhardness in a steel clad layer. In Sun et al. [28], the cladding with AISI 420 stainless steel substrate and satellite 6 clad showed the hardness of the clad is linearly dependent on the percentage of dilution. The hardness decreases linearly with increasing dilution which was due to an altered chemical composition of the clad layer from dilution. Similar results were found by Yellup [29]. The clad hardness of - stellite 6, Cenium Z20, and Eutrolloy – all decreased linearly when the dilution was greater than 10%. When the dilution was less that 10 %, the hardness of the clad was not altered.

Fig. 7 shows that at the melt zone/HAZ interface, a sharp drop in microhardness is experienced. For a low dilution, the hardness dropped to 380Hv. For a high dilution, the hardness dropped to 470Hv. The point measured was at the maximum melt depth of the sample. Since the cooling rate for a high dilution clad is slower than that of a low dilution clad, which means there was no time for grain growth to occur and as a result, a finer microstructure and a higher microhardness was obtained. High dilution had a favorable effect on the microhardness; (i) Clad is less brittle since the hardness was reduced as dilution increases. (ii) A smoother hardness transition occurs at the melted zone/HAZ interface. For low dilution, a high hardness differential is experienced where the hardness sharply drops from 650Hv to 380Hv. This differential of hardness acts as stress concentrator, which will degrade fatigue properties and also cause failure at the interface such as delamination.

3.2.3 The effect of PHT on microhardness

After PHT, both the clad and HAZ hardness decreased by 40% to 400Hv, which was approximately 40Hv below the hardness of the base material (Fig. 8). Since the coarsening of γ in the HAZ still exists, the HAZ maintained the linear increase of hardness, but only from 400Hv to a maximum of 460Hv at the end of the HAZ. A smooth hardness transition is experience at all the interfaces. PHT did not affect the hardness of the base material.

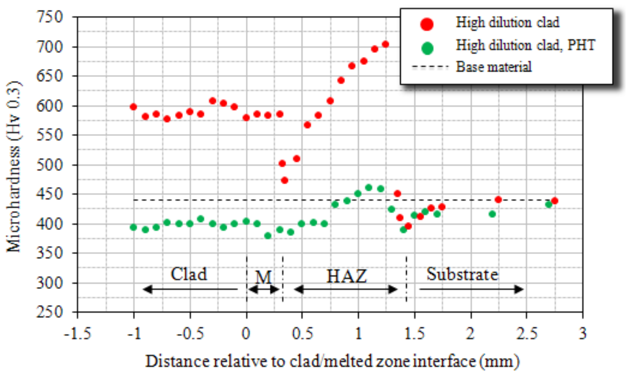

Fig. 8. Vertical microhardness profile, measured relative from the clad/melted zone interface showing the effect of PHT.

4 Conclusion

This study investigated the deposition of AISI 4340 steel powder on AISI 4340 high strength steel plate using laser cladding. Following conclusion can be made:

- The clad layer primarily consists of austenitic dendrites and fine martensitic and bainite structure, while the HAZ contained coarse austenite and an acicular martensitic/ bainitic structure.
- The hardness of the clad is 30-40% higher than the base material.

- Increasing dilution has a favourable effect on the hardness at the melted zone/HAZ interface.
- Increasing dilution from 10% to 30% decreases the average clad hardness from 650 to 580Hv.
- PHT decreased both the clad and HAZ hardness to 400Hv. A smooth hardness transition is experience between clad, HAZ and substrate.

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