Tensile Properties, Microsctructure and Microhardness Analysis of Directly Deposited Waspaloy by Gas Tungsten Arc Welding

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Abstract

Solidification of Waspaloy during Direct Metal Deposition (DMD) by Gas Tungsten Arc Welding (GTAW) process leads to dendritic segregation and interdendritic carbide formation which can strongly influence the mechanical properties of the deposited structure. Heat treatment of DMD parts is the principal means of altering the microstructure and optimizing the mechanical properties. Thus, the main aim of the present study is to investigate the effect of heat treatment on microstructure, microhardness and tensile behaviour of the Waspaloy produced by DMD. The effects of sample location at the transverse directions (parallel to the multilayer wall height) were investigated. The resulting microhardness and tensile test data were compared to the wrought Waspaloy base plate as a baseline. The tensile fracture surfaces were examined to provide insight into fracture mechanisms. The results show that the microhardness and tensile properties of the arc directly deposited Waspaloy depend strongly on the microstructure, which, in turn, is controlled by the deposition process and following the heat treatment conditions. This is particularly the case for properties such as the 0.2% proof stress, which is sensitive function of the distribution of the γ' phase. Solution treatment and double ageing definitely can improve the tensile properties of the deposited Waspaloy. Fracture surfaces of samples tested transverse to the deposition height show fracture by microvoid coalescence which initiated by interdendritic particles.

Keywords: Gas Tungsten Arc Welding, Waspaloy, Microstructure, Microhardness, Tensile Properties.

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Introduction

Considering gas tungsten arc welding (GTAW) as a fusion welding with feed material as an additive manufacturing process, it was seen as a suitable process for the Direct Metal Deposition (DMD) of three-dimensional (3D) structures for repair, feature addition and new component manufacture when equipped with an appropriate manipulation system. Basically, the 3D structure is produced by layer-wise DMD of thin two-dimensional (2D) cross-sections until a final geometry is obtained. This approached has been attempted by Rolls Royce with a commercial name of Shape Metal Deposition [1]. They used arc weld method to build fully dense and near-net-shape structures for aeroengine components. However, these structures are only at the research and development stage. This wire-based DMD concept is still consider in its early stage. Since aeroengine components need to be manufactured with a high degree of integrity and reproducibility, fundamental research is vital to more fully understand the resultant structure-property relationship.

Waspaloy is used mainly for high temperature parts of aerospace engines such as casings, turbine discs and blades [2] due to its ability to retain high strength at high temperatures. It was first developed in the 1940s by one of the United Technologies Corporation subsidiaries, Pratt & Whitney Aircraft, to improve the strength-to-weight ratios at useful service temperatures of up to 954°C of jet engine [3]. Briefly, Ni, Co and Mo are the main elements that give an effect of high temperature strength for Waspaloy through solid solution strengthening. Cr contributes to the oxidation resistance of the alloy. Al and Ti are added to the alloy to form γ' precipitates [4]. Waspaloy can be age-hardened by a standard heat treatment. The objective of applying heat treatment to the Waspaloy is to improve the properties of the material making them more useful and suitable. In order to obtain an optimum microstructure and the desired high temperature properties, these alloys generally require multi-stage heat-treatments [5]. The heat treatment applied to the Waspaloy is expected to eliminate non-uniform composition. The Waspaloy heat treatment for applications such as turbine blades requiring better creep resistance (therefore a coarse grain size) involving a higher solution temperature above the γ' solvus and a longer stabilization exposure. For turbine blade applications, Waspaloy typically receives [6]: 1080°C for 4 hours with air cooling (or faster), 845°C for 24 hours with air cooling and 760°C for 16 hours with air cooling. On the other hand, for optimum room- and high-temperature tensile properties, the following procedures are typically employed [7]: Solution treatment - heat at 995-1035°C/4h/oil quench, stabilization - reheat to 845°C/4h/AC and age harden - reheat to 760°C/16h/AC.

Waspaloy derives its strength from austenitic fcc γ matrix and precipitation hardening of γ′. The γ matrix of Waspaloy is strengthened by the solid solution of Cr and Mo. High Cr content is also an aid for good resistance to corrosive media such as aqueous solutions and acids and Mo is a substitutional solid solution element and interferes with the lattice periodicity, increasing the strength of the alloy i.e. resistance to dislocation movement [8]. The γ′ precipitates have an ordered fcc structure based around the crystal structure $Ni_3(Al,Ti)$. These γ′ precipitates disperse in the γ matrix and act as primary strengthening element to the alloy. The high temperature mechanical properties of Waspaloy are highly dependent on the size and number density of fine, nanometer-size γ′ particles [9]. Carbide is another phase and acts as the secondary strengthening phase in Waspaloy i.e. at the grain boundaries. There are two types of carbides observed in Waspaloy; these are MC and $M_{23}C_6$ [10].

Traditionally, microstructural control is obtained through thermomechanical processing [12]. Generally, this is not an option for DMD material because the parts are net or near-net-shape and one main purpose is to bypass conventional mechanical working techniques. Consequently, heat treatment of DMD parts is the principal means of altering the microstructure and optimizing the mechanical properties. One review claimed that after the solution treatment and the two conventional steps of ageing, cubical shape of MC carbide became slightly spherical, and $M_{23}C6$ carbides were precipitated with a size of about 0.25 µm [2]. It was also observed that the carbides exist in a welded alloy changed from MC type to the $M_{23}C_6$ type following heat treatment, transforming back into their equilibrium state [13]. Mechanical properties of layered DMD material could be affected by the microstructural properties [14]. Mechanical properties of a layered structure could be characterized by means of hardness [15] and tensile testing [16]. After a tensile testing, analysis on the fracture surface also helped in determining the point of weakness in a layered deposition structure [17]. Review showed no evidence of result linking the heat treatment condition and microstructure as well as the mechanical properties of deposited Waspaloy material. The effect of heat treatment on microstructure, microhardness and tensile behaviour of the Waspaloy produced by DMD are vital to be fully understood and analyzed.

The objectives of this study are to perform heat treatment and investigate their effect to the deposited Waspaloy with the aim to introduce homogenous properties and to compare the effect on microstructure, microhardness and tensile behaviour before and after heat treatment processes.

Materials and Methods

Waspaloy walls were deposited onto 10 mm thick Waspaloy base plate using commercially available 1.2 mm diameter welding wire as feedstock. The nominal compositions of wire and base plate are given in Table 1.

Table 1: Nominal compositions of the Waspaloy wire and base plate (in wt.%)

Material	Element (wt.%)							
	Ni	Cr	Co	Mo	Ti	Al	Fe	C
Wire	Bal.	19.1	13.2	4.3	3.0	1.4	0.9	0.1
Base plate	Bal.	19.8	12.8	4.5	3.1	1.4	0.7	0.1

GTAW, a Hitachi Inverter 500GP3 deposition system was used in this study and comprised of an energy delivery system, wire feeding apparatus (Murex Tradesmig 130) and computer numerical control (CNC) for controlling the KR15/2 6-axis robot movement and work table motion. The system also consisted of atmosphere control system including Argon supply and Dasensor (oxygen sensor) and camera system for process control and monitoring. A 3.2 mm diameter tungsten electrode was grounded to conical angle of 60°. The distance between the nozzle head and substrate was set to ~ 15 mm. Parameters as in Table 2 were set into the system prior to the deposition process.

Table 2 The deposition conditions for the DMD of GTAW. Heat input per unit length during deposition using GTAW is 400 J/mm.

Parameter	Peak Current (A)	Base Current (A)	Voltage (V)	Frequency (Hz)	Traverse Speed (m/s)	Wire Feed Rate (m/s)	Step Height (mm)	Work Angle (°)
Values	175	95	10.2	8	0.0035	0.015	1	45

Plates of dimension ~ 120 x 120 mm were built as in Figure 1 and it also shows the position of samples were cut from the deposited plate for heat treatment and tensile testing experiments. The plate was cut at transverse (T) to the deposition build up for top, middle and bottom samples. The samples were subjected to two heat treatment conditions; solution treatment (ST) and solution treatment and double ageing (STA). These heat treatment conditions are ST - heat up for 20K/min to 1080°C for 4 hours and air cooling and STA - solution treatment at 1080°C/4 hours/air cooling, stabilization for 845°C/24 hours/air cooling and ageing for 760°C/16 hours/air cooling. The final dimensions of the tensile testing bar were adapted from BS 4 A.4:1966 with amendments issue of 1993. Gauge length was set to 40 mm. Tensile testing was conducted at room temperature using an Instron 5569 tensile test machine. Test was conducted at rate of 0.6 mm/min with an extensometer attached at the gauge length. The fracture surface was analysed under optical microscope and scanning electron microscope (SEM) to characterise its type of fracture and to identify the location of the fracture-initiating site. Microhardness tests were performed using a LECO M400 Vickers microhardness instrument with a load of 500 gf (i.e. 5 N) applied for 15 seconds. Each sample has undergone standard procedures of specimen preparation i.e. cutting, mounting, polishing, and etching with Kalling's solution and electrolytic-etched with orthophosphoric acid prior to microstructural analysis.

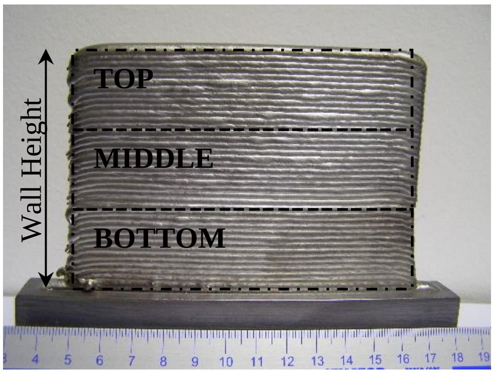

Figure 1 Photograph of the deposited Waspaloy plate showing (a) the top, middle and bottom sections transverse (T) to the build direction

Results and discussion

Microstructure

Solidification of Waspaloy during DMD process leads to dendritic segregation and interdendrtic carbide formation as shown in Figure 2. Secondary electron image of dendrites from the x-z plane of a GTAW build showing dendrite trunks and light contrast of interdendritic MC-type of carbide phase. Hussein et al [18] reports the microstructure formation in Waspaloy multilayer builds following direct metal deposition.

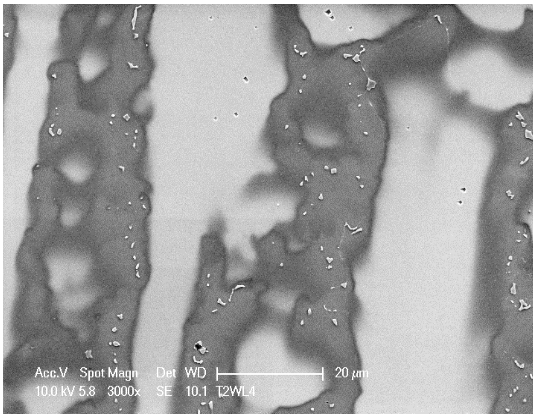

Figure 2: Secondary electron image of dendrites from the x-z plane of a GTAW build showing dendrite trunks and light contrast of interdendritic MC-type of carbide phase.

After ST heat treatment, the dendritic segregation patterns have been significantly reduced due to solid state diffusion. Figure 3 shows that carbide phase was detected along the grain boundaries as well as intragranularly. Energy-disperse X-ray (EDX) spot analysis shows the carbide particles rich with Ti, which indicates the particles was likely to be the MC type of carbides. There was no evidence of γ' precipitates in the solution treated sample. These results are consistent with the observations by Al-Jabra et al [19], who also observed the elimination of microsegregation by dissolution of the constituent into the γ matrix and dissolution of γ' precipitates and most carbide. Following STA heat treatment, grain boundary of STA material is more apparent in the SEM image due to increase of carbide existence in the material following STA. Carbide phase was found at the grain boundaries and intragranularly as shown in Figure 4. EDX spot analysis on the carbide particles at intragranular reveals they have high concentration of Ti, which indicates the particles was likely to be the MC type of carbides. Apparently, some MC carbides remain throughout the heat treatment processes. Whilst at the grain boundaries, the carbides enriched with Cr, which indicates the MC carbides have transformed to $M_{23}C_6$ carbide following the double ageing. There was no evidence of fine scale γ' precipitates formation in the ST samples but significant precipitation was noted in the STA. Sekhar et al [20] also observed substantial increase in the γ' content of Waspaloy aged at the same temperature. A classic solid-state reaction of MC type of carbides is represented by MC + $\gamma \rightarrow M_{23}C_6 + \gamma$'. After ST, the carbides along the grain boundaries were likely to be MC type and grew into discreet irregular shape of 1 μm in size. On the other hand, after stabilization and STA, the carbides transformed to $M_{23}C_6$ type of carbides and grew into a film of ~ 1 μm thick.

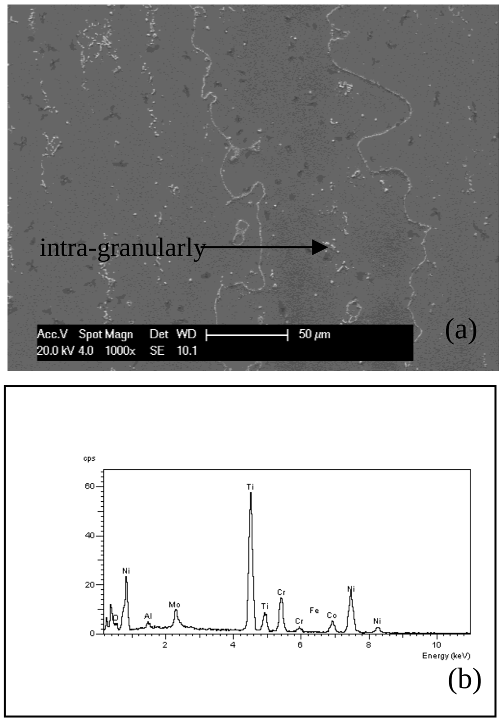

Figure 3: Cross-section at (a) arc deposited Waspaloy plate following STA. EDX analysis on the white particles (b) intragranularly indicates high concentration of Ti and along the grain boundaries indicates high concentration of Cr.

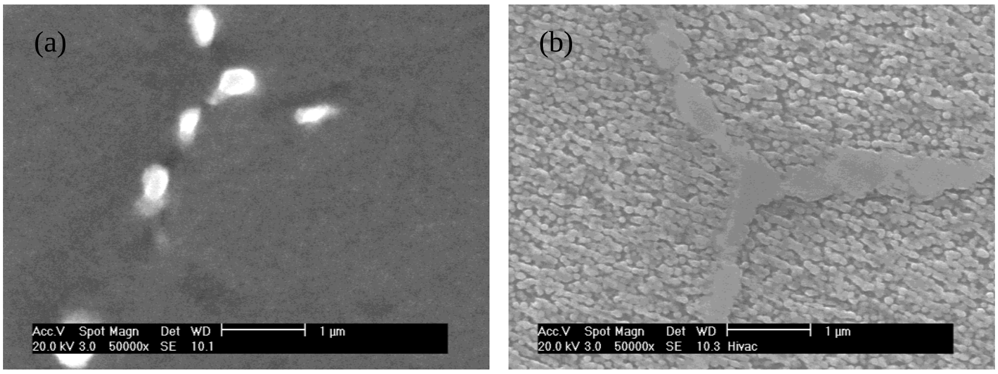

Figure 4: SEM images of middle layer of the arc deposited Waspaloy from following (a) ST and (b) STA showing evidence of γ' precipitates in sample (b).

Microhardness

Microhardness variations of the as-deposited samples were taken at the end portion of the tensile test bar. The ATT (arc, transverse, top) materials gave hardness values of 376 ± 11 and 372 ± 6 kgf/mm^2. Microhardness of the ATM (arc, transverse, middle) samples was 391 ± 13 and 392 ± 12 kgf/mm^2. Whilst, the ATB (arc, transverse, bottom) sections show hardness of 424 ± 16 and 421 ± 12 kgf/mm^2. The results show a clear trend of increasing values from the bottom (ATB) to top (ATT) layers. Following ST heat treatment, the results show almost uniform microhardness was achieved i.e. ~ 375 ± 6 kgf/mm^2. This is close to the hardness of the as-received wrought, WST material i.e. 365 ± 6 kgf/mm^2. Following the STA, the microhardness was further increased, to a value similar to that of as-received wrought, W(STA) material at ~ 424 ± 5 kgf/mm^2. Martin [21] also indicates that hardening would be expected if precipitation took place by nucleation and growth of the phase from solid solution, in which typically found at ageing temperatures. SEM images of the arc deposited Waspaloy from following STA showing evidence of γ’ precipitates in sample, in which contributes to the increase in microhardness value.

Tensile testing

Tensile properties of the arc deposited Waspaloy i.e. ATT, ATM, and ATB shows that modulus of elasticity of the samples varies from 140 to 188 GPa with the ATT and ATM materials have almost similar modulus to each other. The 0.2% PS (proof stress) values range from 682 to 703 MPa. The ultimate tensile strength (UTS) ranges between 945 and 972 MPa with the elongation to failure vary from 19 to 21%. Following ST heat treatment, tensile test properties of the arc deposited AT(ST) material shows the modulus of elasticity of 148 and 178 for the ATB(ST) and ATT(ST), respectively. The 0.2% PS values range from 638 to 672 MPa with the UTS values range from 985 to 1032 MPa and the percentage elongation (%EL) vary between 20 to 22%. Tensile properties of arc deposited Waspaloy tested transverse to the build direction following STA heat treatment shows that the 0.2% PS values range from 716 to 767 MPa. The UTS range from 935 to 1021 MPa. The %EL varies from 5 to 14%.

In the case of arc deposited material, the columnar grain structure produced by directional solidification grains has a well-defined growth direction. The arc deposits have columnar grain structure that has ⟨100⟩ growth direction i.e. almost parallel to the deposition height and tensile axis. It is interesting to note that ATB materials have lower elastic modulus than the ATT and ATM samples. It is evident that the 0.2% PS of ATT, ATM and ATB appears to be different from top to bottom, with ATB having the highest value. The 0.2% PS is related to magnitude of the hardness number [21]. The present work appears to support these statements. These findings confirm that directionally solidified Waspaloy, the stress necessary to cause the onset of plastic deformation by dislocation flow depends strongly with increasing hardening particles of the γ’ precipitates. In the ST heat treatment case, the carbide particles act as keys in obstructing any motion along the slip plane during dislocation under external load. The result is increased elastic limit, hardness and strength [21]. In the case of STA heat treatment, the γ’ precipitates are advantageous for the tensile strength because they resist dislocation [22]. Under the action of external load tending to produce slip i.e. tensile testing, the dispersed γ’ precipitates act as keys, mechanically obstructing any motion along the planes; hence substantially strengthened the alloy.

Fractography

Tensile fracture of the as-deposited material was almost perpendicular to the tensile axis at the width of the test bar but shear approximately 45° at the thickness of the test bar. The overall morphology of the fracture surfaces of the ATT, ATM and ATB exhibit a clear dendritic pattern with cruciform shape and grain boundary cracking; dimples with microscopic voids indicative of ductile fracture. MC type of carbides was observed in the dimples.

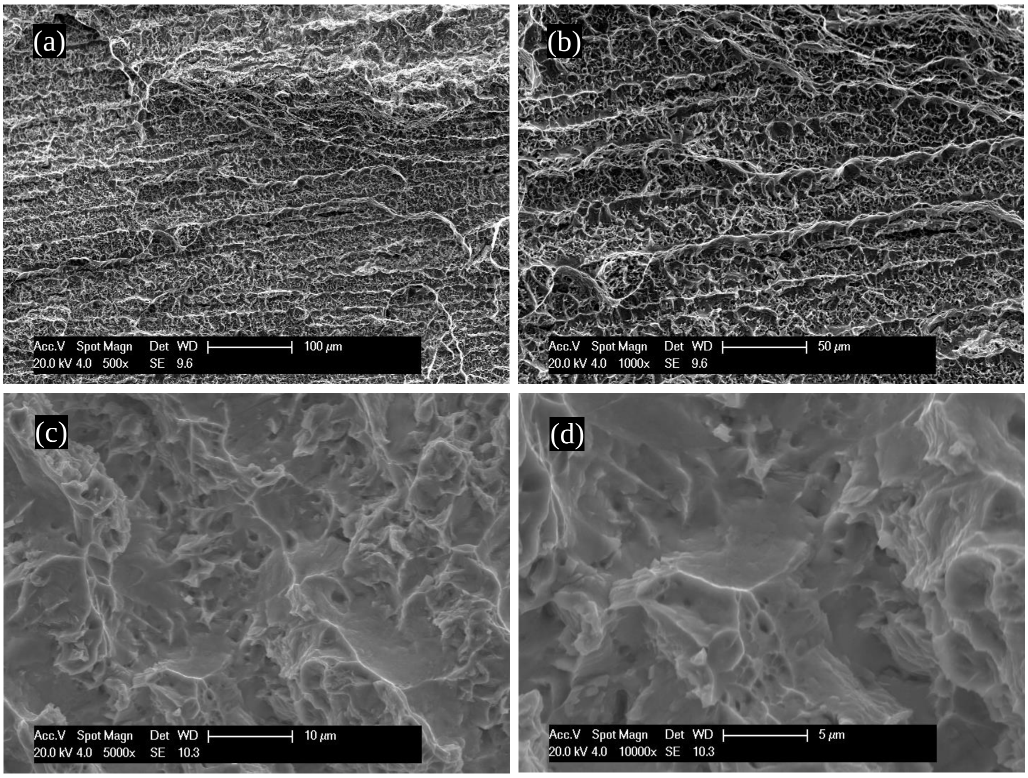

Figure 5: SEM micrographs showing fracture surface features of ATB material. The fracture surface exhibit: (a-b) a clear dendritic pattern with cruciform shape and grain boundary cracking; (c-d) dimples with microscopic voids indicative of ductile fracture. MC type of carbides was observed in the dimples.

Following ST heat treatment, similar, the fracture surface of the samples was also sheared with an inclination of ~45° to the tensile stress. The overall morphology of the fracture surface sample exhibit similar feature which showing dendritic pattern although dendrites were significantly reduced after the solution treatment. Interdendritic cracking by grain boundary MC type of carbides and dimples with microscopic voids which indicate ductile fracture could be observed in the materials. Following the STA heat treatment, the overall morphology of the fracture surfaces exhibits features which showing dendritic 'ghost' pattern. The dendrites were significantly reduced after the solution treatment. Formation of the dendritic 'ghost' pattern in the fracture surface might due to the carbide phase in the interdendritic region. Terminology of 'ghost' pattern is also applied by Lippold [23]. Interdendritic cracking could be observed in the materials. The $M_{23}C_6$ type of carbides was detected at the fracture surface. Dimples with microscopic voids indicating ductile fracture and particles observed in the dimples are most likely to be the fine γ' precipitates.

Conclusion

Conclusion that can be drawn from this study are:

- Microstructure of the as-deposited Waspaloy changed according to the heat treatment process. After ST heat treatment, the dendritic segregation patterns have been significantly reduced due to solid state diffusion, MC type of carbides were observed and there was no evidence of γ' precipitates. Following STA heat treatment, $M_{23}C_6$ carbide formed at the grain boundaries, MC type of carbides were detected intra-granularly and γ' precipitation was significant.

- Microhardness of the deposited plates is substantially affected by the deposition process. Thermal cycle above the critical temperature of γ' precipitates allows the precipitates to form and grow in size, thus the higher hardness.
- Modulus of elasticity is strongly depending on the crystallography structures and orientations.
- The 0.2% PS varies according to the microhardness results. Stress that necessary to cause plastic deformation is sensitive to the formation of γ' precipitates.
- Solution treatment above the critical temperature of the γ' precipitates causes dissolution of elements (thus eliminating the dendritic structure), γ' precipitates and most carbide into the γ matrix giving an exceptionally ductile structure.
- Solution treatment and double ageing gave a marked improvement in the hardness values by reprecipitation fine γ' phase. This also resulted in a large improvement in the 0.2% PS values but with a decrease in the ductility values.
- The overall morphology of the fracture surfaces of the arc deposited Waspaloy exhibit a clear dendritic pattern with cruciform shape and grain boundary cracking. Dimples with microscopic voids indicative of ductile fracture.

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Author Contributions

All authors contributed towards data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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