Effect of post weld heat treatment on microstructure, mechanical properties and corrosion behaviour of AA6351 Gas Tungsten Arc welds

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ABSTRACT
Aluminium AA6351 alloy is extensively used for defense and marine applications due to a better combination of strength to weight ratio and corrosion resistance. Welding is a commonly used fabrication process for manufacturing components required for shipbuilding and defense applications. The welding process affects mechanical properties and corrosion resistance because of microstructural changes in various zones of welds. In the present work, an attempt has been made to study the effect of post weld heat treatment (PWHT) of solutionising followed by ageing at 177^0 C for 8hrs on AA6351 welds made using Gas Tungsten Arc Welding (GTAW) process. This study comprises the mechanical and pitting corrosion behavior of as welded and post weld heat treated samples with respect to the microstructural changes. Microstructural studies were carried out using optical, scanning electron microscopy (with EDS) and X-ray diffraction (XRD) for various zones like fusion zone (FZ), heat affected zone (HAZ) of welded AA6351 plates. Micro-vickers hardness (at 500g load) and tensile test was carried out to analysis mechanical behaviour. Similarly, potentio-dynamic polarization testing was carried out in various zones present in the welds to understand the pitting corrosion behavior. Results revealed that the PWH treated GTA welds of AA6351 alloy exhibited a better combination of mechanical properties and corrosion resistance.

Keywords-AA6351; GTAW; PWHT; SEM; mechanical properties; corrosion resistance;pitting.

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1. INTRODUCTION

AA6351 is an aluminum alloy that contains magnesium and silicon as its primary alloying elements. It is a heat-treatable alloy with high strength and corrosion resistance which making it a desirable material for various applications in the fields of construction, transportation, marine and aerospace [1-3, 12]. Welding is used as major fabrication technique for AA6351 among several methods such as casting, forming, extrusion etc. The welding metallurgy of AA6351 is concerned with understanding the microstructure, properties, and processing of the alloy. The microstructure of AA6351 is composed of α-aluminum solid solution, magnesium silicide (Mg_2Si) particles, and various intermetallic phases such as Al_4MnSi, Mg_5Si_6, and $Mg_5Al_2Si_4$ [1]. These phases contribute to the strengthening of the alloy through various strengthening mechanisms such as solid solution strengthening, precipitation strengthening, and grain refinement. Though AA6351 is generally considered to have good weldability, but it is prone to hot cracking, shrinkage and porosity if proper welding procedures are not followed. The high magnesium content can cause hot cracking, especially when welding thick sections or using high heat inputs. The use of filler alloys with lower magnesium content and proper preheating and post-weld heat treatment (PWHT) can reduce the risk of hot cracking and porosity.Post weld heat treatments are done to further refine the microstructure and strengthening phases which enhances the strength and ductility to improve the mechanical properties [6-8, 14, 15]. Fageehi et al. reported that ageing at 160^0 C increased the surface hardness and corrosion resistance. Ahmed et al. studied the influence of post weld heat treatment on mechanical properties of AA6351 with various ageing techniques, which resulted improvement in yield strength and % of elongation at peak ageing condition (160^0 C, 18hrs) [1]. Sreeharan et al. investigated the effect of ageing at 185^0 C for 6hrs which developed welds with better hardness and tensile strength with brittle failure [19]. As the choice of processing conditions and heat treatment parameters will be crucial to get the desired properties of the final product, present work is intended to compare and correlate the influence of GTAW and PWHT on the mechanical properties and corrosion behavior of AA6351 aluminium alloy welds with microstructure changes.

2. EXPERIMENTAL PROCEDURE

In the present study, AA6351-T6 aluminum alloy plates with the dimensions of 150 x 60 mm and a thickness of 6 mm were used for welding. GTA welding process was performed using 2mm diameter ER4043 Al-Si filler wire, and 99.99% pure argon gas with a current of 157A and voltage of 20 V. Post-weld heat treatment (PWHT) was conducted on the welded joint samples, which included solution treatment and artificial aging. The solution treatment was performed by heating the samples to 523°C for a soaking period of 30 min, followed by quenching in cold water bath. After that, the samples were subjected to artificial aging at 177°C for 8 hours. The microstructures of different zones of welds were examined using a Olympus optical microscope, scanning electron microscopy equipped with energy dispersive spectroscopy (EDS) and XRD was used for further analysis of microstructure. Vickers micro-hardness tests were conducted across the weld using a load of 500 grams, and the tensile test was conducted using an INSTRON tensile testing machine. Potentio-dynamic polarization studies were carried out on the weld specimens in aerated 3.5% NaCl solution with pH adjusted to 10.0 to analyze the pitting corrosion behavior of the base metal, fusion zone, and heat-affected zones of welded specimens. A Gill AC electrochemical system was used to study the pitting corrosion behavior of the specimens, and those that exhibited a relatively more positive Epit (or less negative Epit) were considered less susceptible to pitting corrosion.

3. RESULTS AND DISCUSSIONS

Microstructural studies:

Fig 1 shows the optical microstructure of AA6351 base metal in as welded and PWH treated condition. The elongated grains of α-Al matrix in dark color and secondary phase (β- Mg_2Si) which is in light color was observed in both as welded and PWH treated condition, from the above microstructures. And also more amount of secondary phase (β- Mg_2Si) was observed from the Fig 1b, with evident light color phase which can be attributed to solutionizing and ageing during PWHT. From the Fig 2, as welded HAZ shows coarse columnar grain structure whereas PWH treated sample clearly shows the homogeneity throughout the microstructure with uniform distribution of secondary phase and definite features. In general, most alloyingelements have limited terminal solid solubility in aluminum. Due to lower solid solubility, dendrites which are the first structures to form during the process of solidification, will contain relatively small amount of solutes. As a result, inter-dendritic networks are formed around these dendrites, which may include one or more secondary phases. The secondary phase which appear in black color at interface and weld zone microstructures are more likely to be Mg_2Si [4-5, 8, 18] (Fig 4). Fig 2c depicts the fine grain size, small isolated intra-dendritic droplets in the weld zone with inchoate dendrite arms. During GTAW the dissolution of fine precipitates, partial dissolution of secondary phase and cooling rate involved with GTAW are may be the reason for as welded sample with higher heterogeneity in the microstructure of different zones with scattered secondary phase than PWHT sample. The PWH treated weld zone contains the equiaxed grain structure and clearly shows the absence of intra-dendritic droplets may due to dissolution (Fig 2f).

The SEM photographs of the weld zone shows the coarser grain size in as welded condition with acicular morphology compared to PWHT condition with uniform distribution of secondary phase (Fig 3) [18]. And also the clusters of light phase in Fig 3a, can be interpreted as Mg2Si, with support of analyzed data from Fig 4 [11, 18]. As the phenomenon of clustering results due to micro-segregation, it promotes the formation of localized precipitation free zones which are detrimental to the mechanical and corrosion behavior. The elemental mapping of weld zone shows clustering and element free zones in the microstructure of as weld sample. Whereas the PWH treated sample shows uniform distribution of elements in the entire microstructure of PWHT condition with absence of clustering as well as element free zones. From that, increase in the density of precipitation can be observed in PWH treated sample when compared to as weld sample.

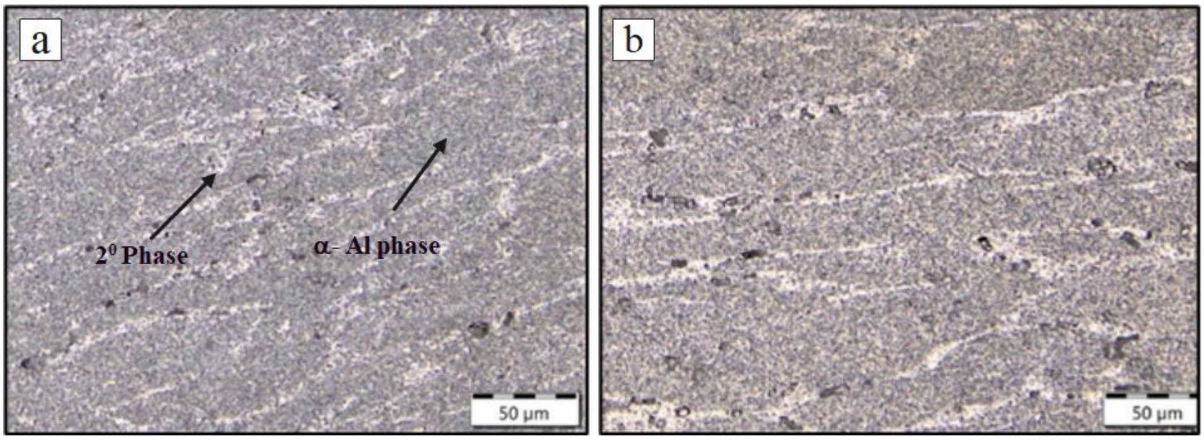

Fig 1. Optical Photographs of AA6351 base metal a) before PWHT b) after PWHT

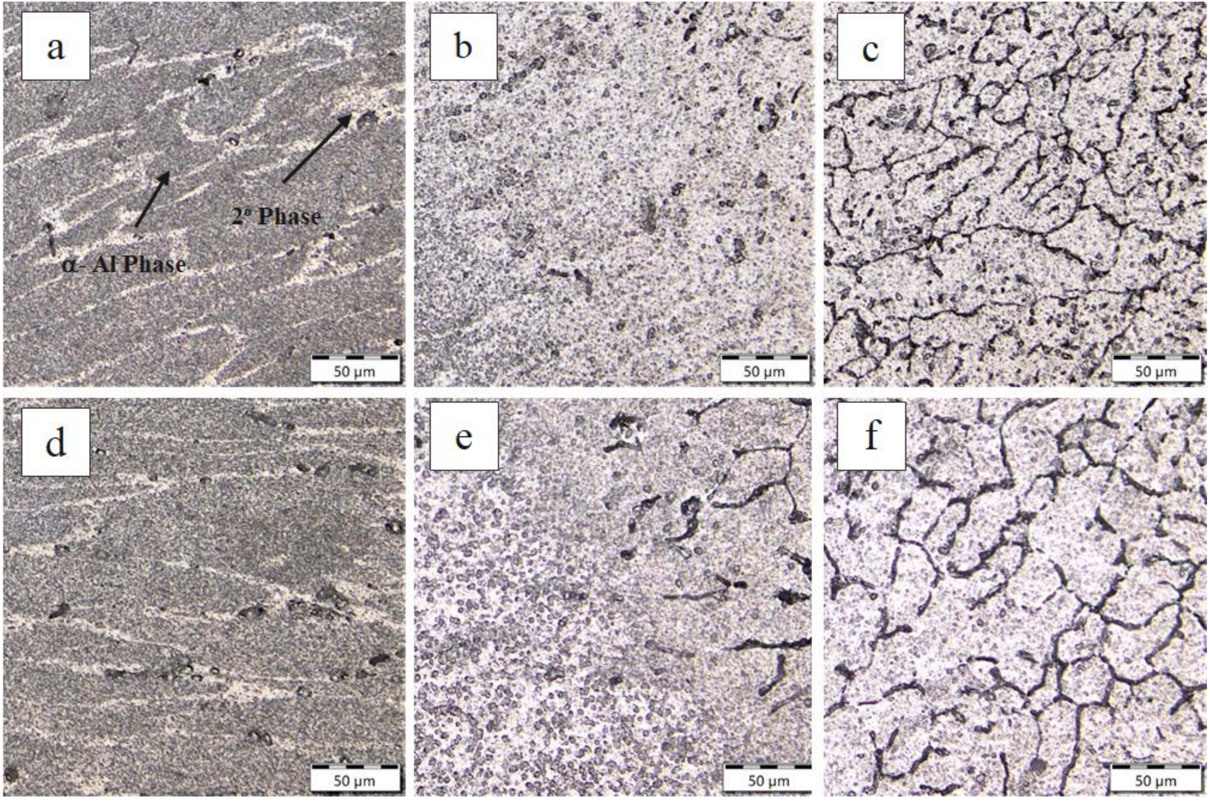

Fig 2. Optical Photographs of AA6351 GTA weld, as weld condition -a) HAZ b) interface c) WZ, PWHT condition d) HAZ e) interface f) WZ

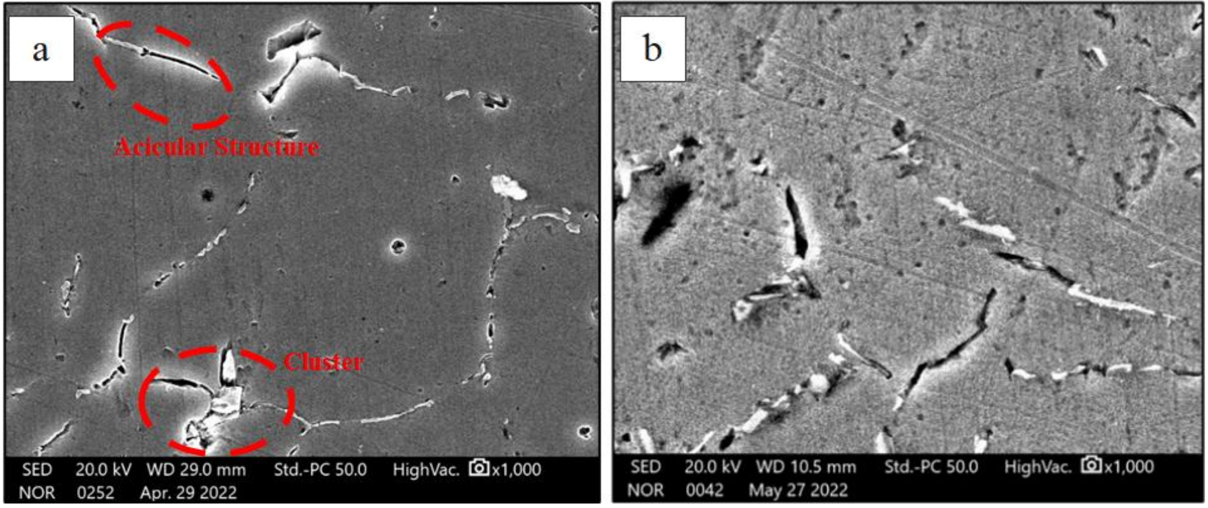

Fig 3. SEM photographs of AA6351 GTA weld, weld zone a) as weld b) PWHT

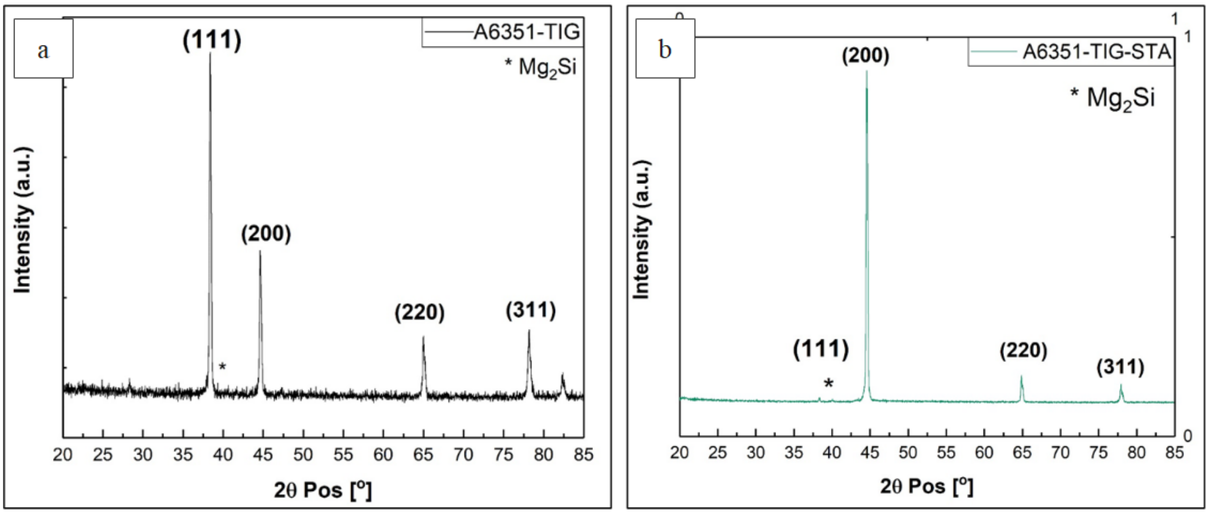

Fig4. X-ray diffraction spectrum of AA6351 GTA weld a) as weld b) PWHT

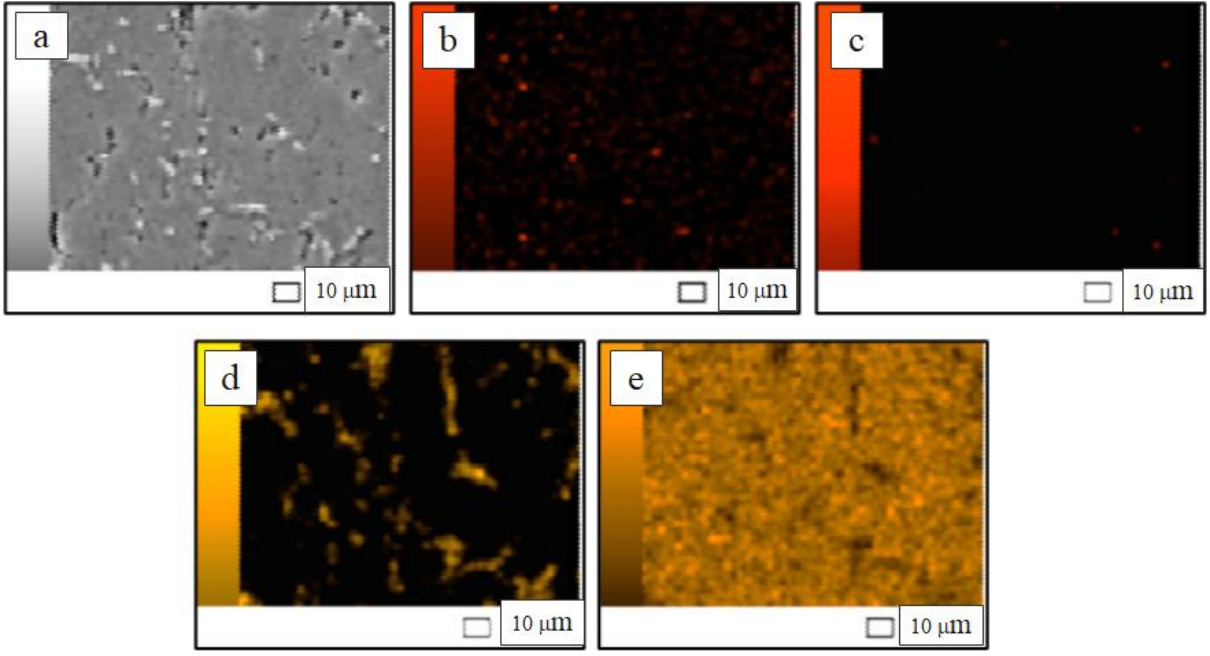

Fig 5. Elemental mapping of AA6351 GTA weld zone in as weld condition a)Ref.image b) Mg c) Mn d) Si e) Al

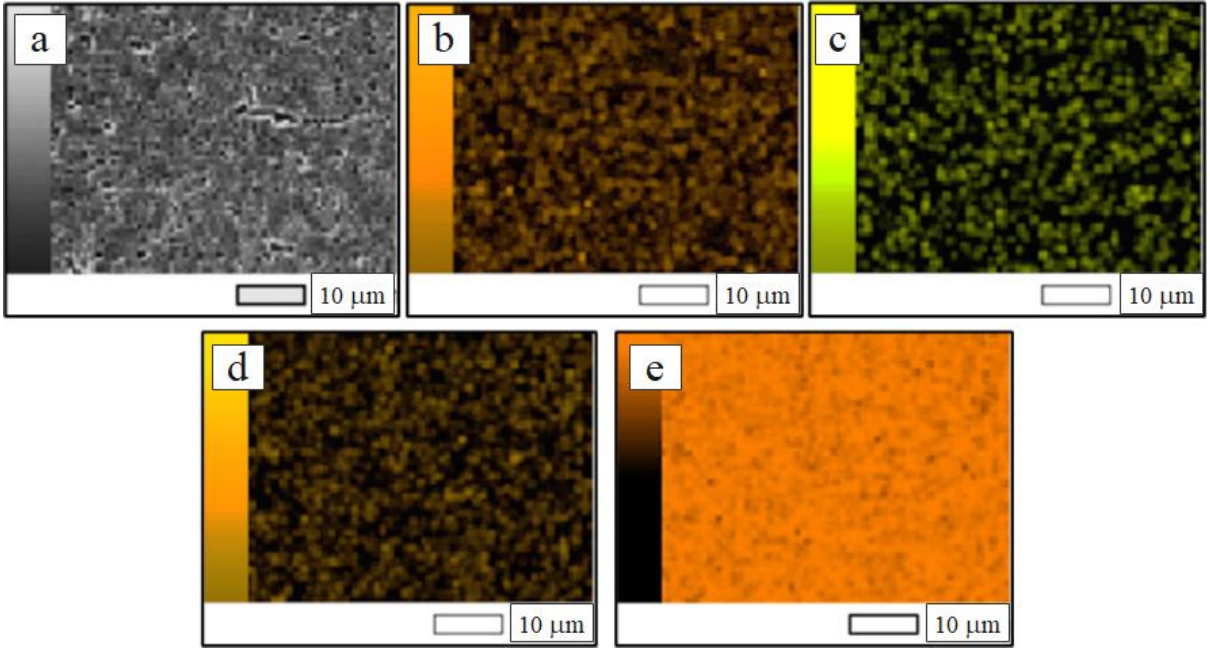

Fig 6. Elemental mapping of AA6351 GTA weld zone in PWHT condition a)Ref.image b) Mg c) Mn d) Si e) Al

Mechanical properties:

Tensile studies:

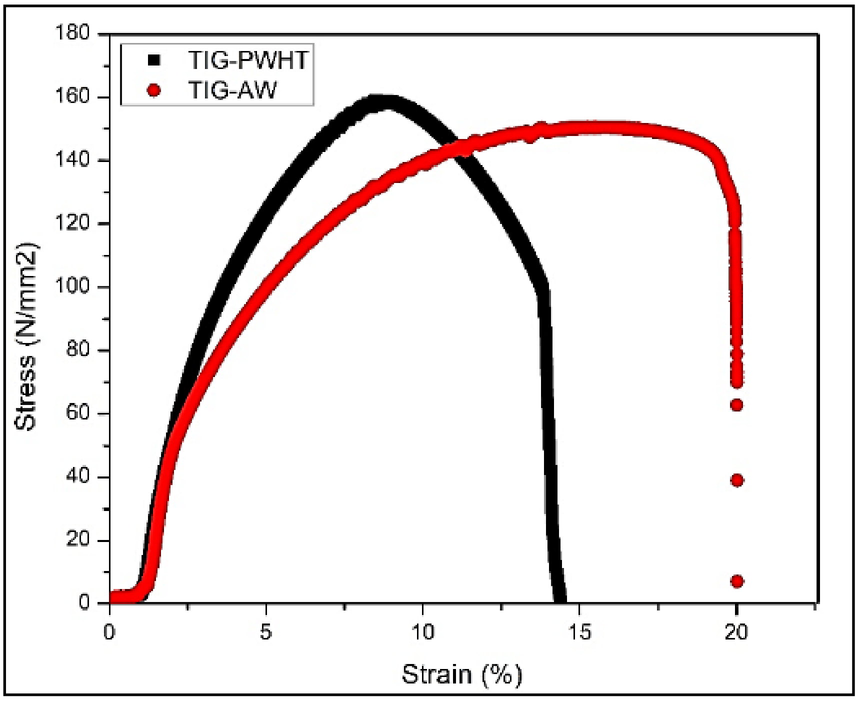

Fig 7. Tensile graph of AA6351 GTA Welds

Table 1. Tensile values of AA6351 GTA Welds

Weld/Joint	Yield strength (MPa)	Tensile strength(MPa)	Elongation(%)	Fracture location
As welded	56.7614	150.574	13.3800	HAZ
PWHT	58.7596	159.846	11.7000	Weld center

The tensile properties of as welded and PWHT sample are given in Table 1. PWH treated sample shows the better tensile properties compared to as weld sample. Improvement in the tensile strength of PWHT sample may be due to precipitation hardening phenomenon, where moving dislocation interacts with precipitate and absorbs more energy for further dislocation motion. It may be due to enhanced volume fraction of precipitation during PWHT, which also effects % of elongation. Thedissolution of finer precipitates as well as partial dissolution of secondary phases during welding and segregation along grain boundaries may be responsible for low tensile strength value of as welded sample compared to PWHT sample [10, 16-17]. As HAZ experiences temperature around 490-548^0 C while welding, HAZ is more prone to segregation and formation of brittle network along grain boundaries. As brittle networks are responsible for generation of micro cracks, the fracture location at HAZ evidently proves the above, in case of as welded sample (Table 1) [9]. From fig. 8, the fracture surface of as welded sample shows the 40% dimpled and 60% shear fracture. The undissolved precipitates may be the reason for dimple fracture. And also dislocation pile-up at grain boundaries with brittle network may resulted in the creation voids due to de-cohesion. The growth of formed voids may leads to the trans-granular dimple fracture. The PWHT sample shown the nearly 80% inter-granular fracture and 20% of dimple fracture. Small fraction of voids are observed in PWHT sample compared to as weld sample and may be due to very less amount of brittle networks at grain boundaries due to dissolution of brittle networks during PWHT.

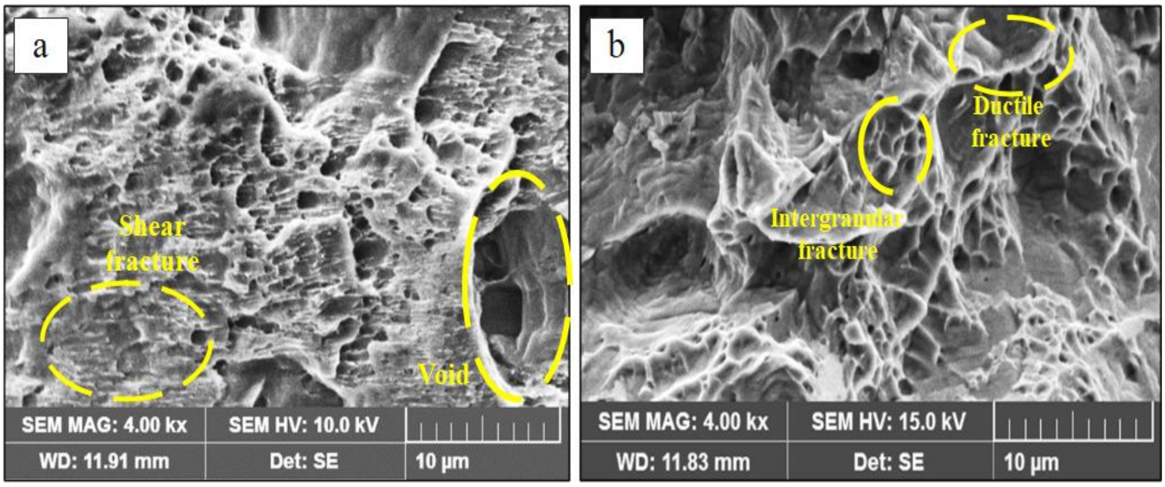

Fig 8. Fracture surface of AA6351 GTA Weld a) as weld b) PWHT

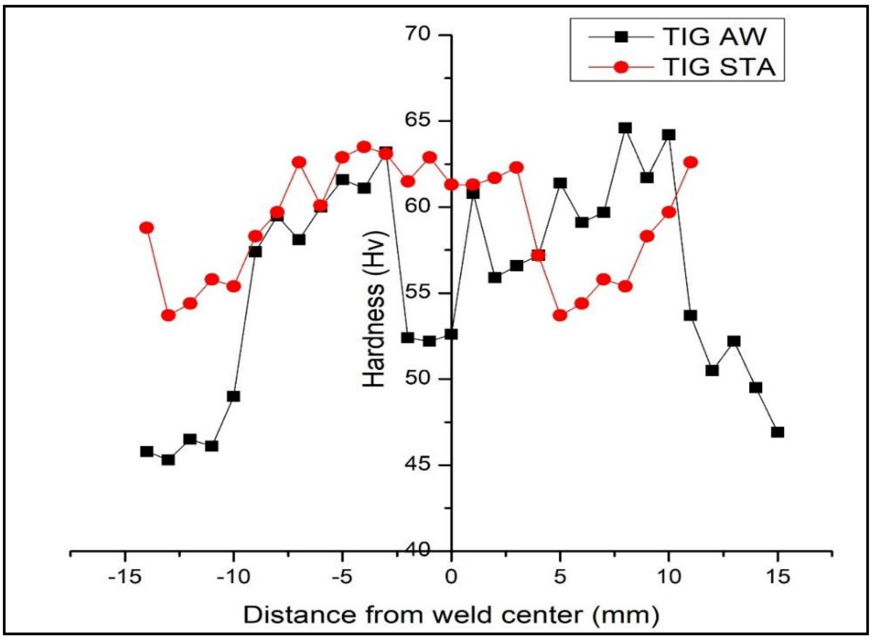

Fig 9. MicroVickers hardness graph of AA6351 GTA Welds

Hardness Studies:

Table 2. Micro-Vickers hardness values of AA6351 GTAW as weld and PWHT

TYPE OF THE WELD	BASE METAL	HAZ	WELD ZONE
As weld	50	56	54
PWHT	59	60	62

Among the hardness values of as weld and PWHT samples, PWHT sample exhibited higher hardness compared to as weld. From the Table 2, base metal in as weld sample shows the less hardness value compared to other zones, and HAZ shows the higher value. Equiaxed grain structure contained weld zone of PWHT sample shown maximum hardness value compared to other zones, whereas as welded sample weld zone shows coarse columnar grains. And also less gradient in the hardness values of various zones of PWHT weld joint improves the joint efficiency. The increased volume fraction of precipitation during PWHT and their uniform distribution might have resulted in enhanced hardness values. The dissolution of brittle networks, inter-dendritic droplets during PWHT may also take part in the improved hardness [18]. The microstructure heterogeneity in terms of clustering and Silicon segregation at grain boundaries plays major role in the lower hardness values of as weld sample.

Corrosion studies:

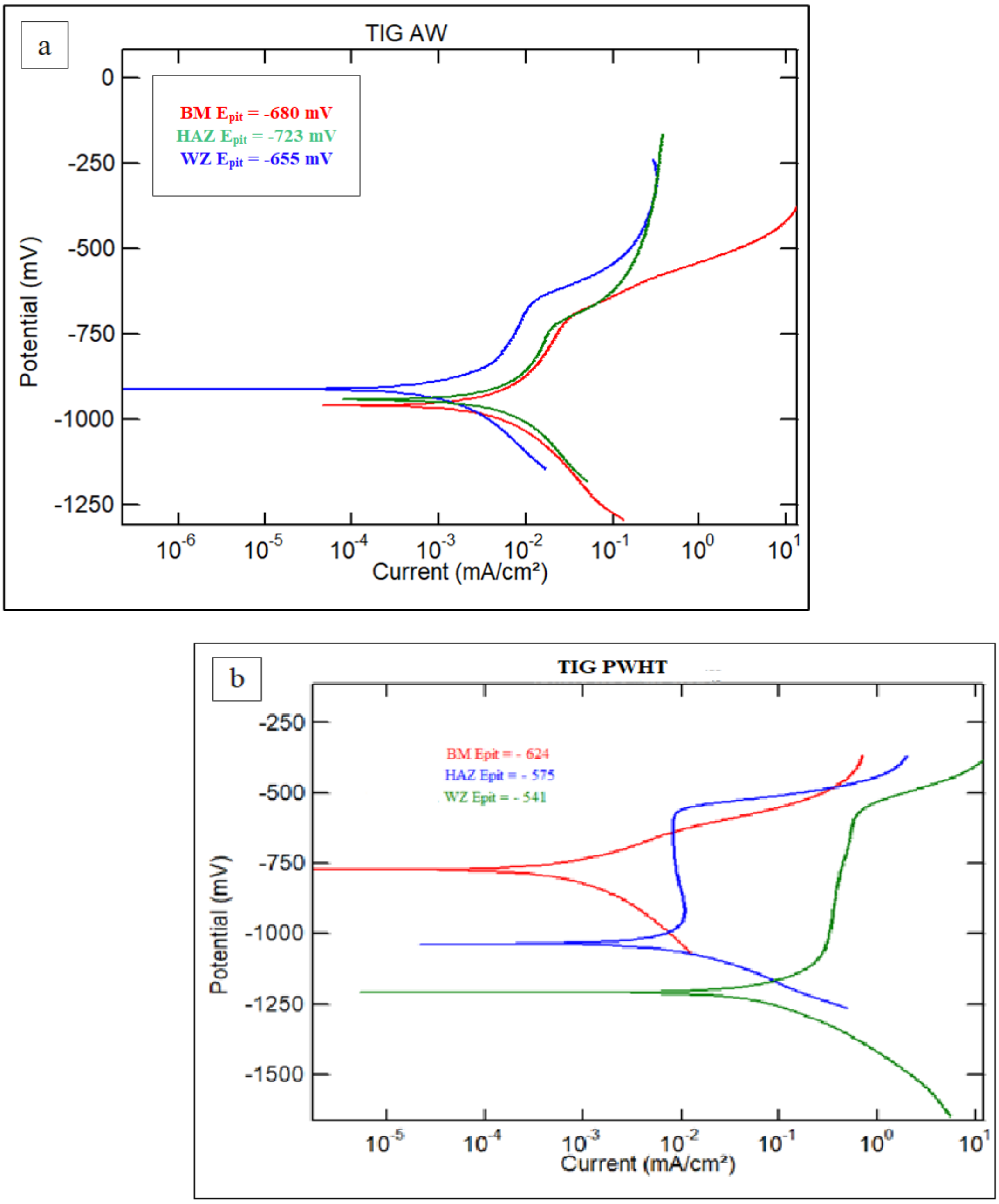

Fig 10. Potentiodynamic polarization curves of AA6351 GTA Welds a) as weld, b) PWHT

From Fig 10, it is observed that the PWHT weld zone ($\mathrm{Epit} = -541 mV$) was more corrosion resistant than the as weld sample weld zone ($\mathrm{Epit} = -655\, mV$). The dissolution of precipitates and segregation at grain boundaries which results in formation of precipitate free zone (PFZ) has lead to the lower corrosion resistance. As the partially dissolved secondary phase and PFZs forms localized galvanic coupling which facilitates the severe corrosion may reason for lower corrosion resistance of as weld sample [13]. The preferential grain boundary corrosion which happens due to segregation at grain boundaries as well as sub-grain boundary corrosion which takes place due to clustering which generally seen in precipitation hardenable alloys are detrimental to the corrosion resistance of weld joint. After undergoing PWHT, samples exhibit better corrosion resistance due to the achieving the chemical homogeneity during solutionizing and uniform reprecipitation and redistribution of precipitates throughout the microstructure during ageing. This results in coherent and uniform precipitation, which is responsible for the improved corrosion resistance of

PWH-treated samples. Whereas in as-welded sample, due to dissolved and non-uniform precipitates, more negative E_{pit} values were recorded which can be evidently seen in case of HAZ (E_{pit}= -723mV). Fig. 9 (a) shows that the WZ of the as welded sample resulted in enhanced pitting corrosion resistance. It can be attributed to complete dissolution of secondary phase, as weld zone experiences the high temperatures during welding. The replacement of coarse columnar grains with uniform finer equiaxed grains are observed in the microstructure of the WZ of the PWHT sample. Results established that WZ of PWHT samples exhibit better pitting corrosion resistance due to the absence of precipitate free zones at the interface and uniform redistribution of re-precipitated secondary phase. Polarization curves of as-welded base metal and PWHT base metal are also shown in Fig. 10. As solutionized samples exhibit homogeneous precipitation during ageing the base metal of PWHT samples shows better-pitting resistance than the base metal of as-welded samples.

4. SUMMARY AND CONCLUSIONS

In the present study, a comparison was made between the microstructure, mechanical and corrosion behavior of AA6351 (GTA weld) in as welded condition and PWH treated condition. The following are the most important conclusions drawn from the present investigation.

1. The microstructure of as welded condition depicts the dissolution of finer precipitates, partial dissolution of secondary phases which resulted in formation of PFZs. Whereas PWH treated sample shows the homogeneity in the microstructure with uniform reprecipitation because of PWHT (solutionizing and ageing).

2. The PWH treated sample has shown superior mechanical properties than as welded sample with increased volume fraction of precipitation and their uniform distribution played significant role in influencing the properties, and resulted in better mechanical behavior with increased yield and tensile strength.

3. The as welded sample shows the lower corrosion resistance and may due to the galvanic coupling between α-Al matrix and β-Mg_2Si mainly, PWH treated sample shown better corrosion resistance through presence of coherent precipitates

4. The overall mechanical and corrosion behaviour of PWH treated GTA weld joint shown better results compared to as weld joint, with less gradient in hardness values, better combination of mechanical properties and corrosion resistance.

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