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Contributed Paper

Effect of Postweld Heat Treatments on TIG-Welded Microstructures of Superalloy, IN - 738

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ABSTRACT

This research has an aim to search for the optimal heat treatment condition after TIG welding to refurbish fractured turbine blade (cast nickel-based superalloy grade Inconel 738) of land-based gas turbine engines with the most proper final microstructural characteristics. The Inconel 738 (IN-738) specimens were welded by TIG welding process together then various heat treatment conditions were applied in order to reach the proper microstructure with uniform distribution of proper size of intermetallic phase, namely, gamma prime (γ') in the metal matrix, for high performance in mechanical properties at elevated temperatures. The heat treatments consist of solutioning, primary aging and secondary aging at different heating temperatures. From the results, it was found that the postweld heat treatment provided both beneficial and detrimental effects depending on initial reheat treatment condition. The lowest solutioning temperature (1398 K) after weld process provided the most coarsening size of γ' particles in uniform dispersion in base metal zone as well as uniform dispersion of very fine γ' particles in heat affected zone (HAZ) with very high area fraction. Furthermore, the higher solutioning temperatures after weld process resulted in smaller size of γ' particles precipitating in both HAZ and base metal zone. The highest solutioning temperature of 1478 K resulted in hot cracking in base metal zone near weld band.

Keywords: TIG welding, reheat treatment, microstructural repair, gamma prime particles, and nickel-based superalloy.

1. INTRODUCTION

This research work presents a route of an applied research for repairing turbine blades (which were made of a very expensive cast nickel base superalloy) by welding and post-weld heat treatment processes, which are possible to be performed in Thailand for rejuvenation of superalloy components in land-based gas turbine industry, especially power plants in Thailand. The increasing of usage and success of the gas turbine power-generation industry in Thailand is strongly dependent upon satisfying the demands of a range of customers and operators and by arising from a number of market and legislative factors such as capital costs, operational costs, efficiency, power output, fuels, emission (to environment) and so on.

Therefore, the operators or electricity

generating producers require their own maintenance and repairing. They also need a wide range of materials engineering knowledge and skills to ensure safety, reliable operation of the engines as well as costs. However, in Thailand, there are still very few applied researches and developments related to this field. The country, by electricity producers, has lost lots of money every year to purchase new expensive superalloy components from abroad and/or has to dispatch long-term serviced components to abroad for repairs. Therefore, many research works try to reach methods for repairing superalloy components in Thailand. However, there is no research work, especially dealing with superalloy refurbishment by TIG welding and post-weld heat treatment, especially for IN-738.

The aim of this research work is to determine the most suitable and practicable repairing condition, which provides the proper microstructural characteristics and phase stability by TIG welding process method with various postweld heat treatments for long-term exposed gas turbine blades, casting nickel base superalloy, grade IN-738 after long-term service operated by Electricity Generating of Thailand (EGAT). The cast nickel base superalloy IN-738 is widely used as a blade material in the first row high-pressure stage of gas turbines. The alloy contains refractory elements such as Mo, W, Ta, Cr and Co to prevent local hot corrosion [1]. The alloy has a multi-phase microstructure consisting FCC γ matrix, bi-modal γ' precipitates (primary and secondary), γ-γ' eutectic, carbides and a small amount of deleterious phases such as σ, δ, η and Laves. The total weight percent of γ' in IN-738 superalloy is approximately about 60%. Therefore, the high temperature strength of the alloy depends strongly on properties of all phases [2-6].

This TIG welding affects a metallurgical bond between the respective components. Furthermore, this leads to a cast structure of variable size and properties depending mainly on the metals being welded. Welding leads to dissolution of the hardening phase and their re-precipitation in less desirable physical form in the matrix. The essence of using joining process on precipitation-hardened superalloy is to find a way to keep the high strength associated with γ'- hardened, which contains proper size, shape and area fraction from being lost became of the welding process. There are many research works [7-11] studying and evaluating the TIG welding for IN-738. However, no one deals with effect of postweld heat treatment (PWHT) on its microstructure, which this present work does.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

The cast nickel base superalloy in this study was Inconel-738 (IN-738), with the following compositions (wt.%); 15.84%Cr, 8.5%Co, 3.47%Ti, 3.46%Al, 2.48%W, 1.88%Mo, 1.69%Ta, 0.92%Nb, 0.11%C, 0.07%Fe, 0.12%B, 0.04%Zr and balanced nickel.

All sectioned samples, after each TIG welding with IN-617 weld filler followed by postweld heat treatment, as shown all details in Table 1 were ground and polished using standard metallographic techniques and were subsequently etched in a marble etchant, which has chemical compositions as follows; 10 g. $CuSO_4$, 50 ml HCl, and 50 ml H_2O. The microstructures of reheat-treated samples were viewed using scanning electron microscope (SEM) in the secondary electron mode. The size and area fraction of gamma prime particles were determined by the image analysis software.

3. RESULTS AND DISCUSSION

In general, superalloys with low

aluminum and titanium contents can be welded with little difficulty. Furthermore, superalloys with a slow aging reaction also are welded without problem [12]. However, in this research study, most welding concern is concentrated on the high strength γ'- hardened cast nickel base superalloy, IN-738, which consisting of high precipitation hardener (aluminum and titanium) content alloy. The welding procedure in the alloy depends on the mechanism by which they are strengthened for high temperature service with both solid solution strengthening and precipitation strengthening utilized. The welding relies on melting and solidification of base alloy plus a filler that has a composition compatible with the chemistry of the components being employed both environmentally (corrosion, oxidation etc.) and mechanically (acceptable strength of both low and high temperatures) with no need of the composition of any of the components being joined [10-12].

The alloy was TIG weld in the solution annealed condition and subsequently heat treated to precipitate the second phase on a two aging steps. The results of TIG weld followed by various heat treatments are listed below:

3.1 Weld Band and Metal Filler

Figures 1a) and 1b) show the selected weld microstructures of specimens after different postweld heat treatment conditions No. 1 and 12, respectively (see Table 1). The base metal of IN-738 lacates on left side of each figure and filler metal locates on right side of the figures. Weld band locate in the middle between the base and filler metals. All zones are cast structure where base metal consists of many carbides (white phase). Figures 1c) and 1d) show the weld band structure with very high magnification. It should be noted that coarse γ' particles locate near base metal and very fine γ' particles locate in opposite side or in weld filler zone. However, it was also found that the difference

Table 1. Heat treatment conditions after TIG welding process.

No.	Solution annealing	Primary precipitate aging	Secondary precipitate aging
1*	1398 K / 7.2 ks (AC)	————————	1118 K / 86.4 ks (AC)
2	1398 K / 7.2 ks (AC)	1198 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
3	1398 K / 7.2 ks (AC)	1328 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
4	1423 K / 7.2 ks (AC)	————————	1118 K / 86.4 ks (AC)
5	1423 K / 7.2 ks (AC)	1198 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
6	1423 K / 7.2 ks (AC)	1328 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
7	1448 K / 7.2 ks (AC)	————————	1118 K / 86.4 ks (AC)
8	1448 K / 7.2 ks (AC)	1198 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
9	1448 K / 7.2 ks (AC)	1328 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
10	1478 K / 7.2 ks (AC)	————————	1118 K / 86.4 ks (AC)
11	1478 K / 7.2 ks (AC)	1198 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)
12	1478 K / 7.2 ks (AC)	1328 K / 3.6 ks (AC)	1118 K / 86.4 ks (AC)

*Standard heat treatment condition.

in γ' particle size between coarse and very fine particles decreased when solutioning temperature was increased. This led γ' particle forming atoms could diffuse in more amount and/or more far distance from base metal zone to weld filler zone after all γ' particles completely dissolved during higher temperature solutioning step and finally reprecipitate in uniform size after agings. This also occurred in weld filler zone near weld band, as shown in Figures 1e) and 1f).

3.2 Base Metal Zone

From Figures 2a-2l, it could be summarized that:

With lowest solutioning temperature of 1398K, the average final sizes of γ' particles from heat treatment conditions No.1-3, as shown in Figures 2a-2c, are biggest comparing to those of other higher solutioning temperatures. This was due to that the previous coarse γ' particles could not be completely dissolved by such low solutioning temperature. It could dissolve these coarse γ' particles in some degree. It seems that primary precipitate aging could influence on the slightly coarser γ' particle size after solutioning, which higher aging temperature provided the bigger size of γ' particles. It should be noted that primary precipitate aging could increase the average area fraction of these precipitates as well.

With solutioning temperature of 1423 K in heat treatment conditions No.4-6, as shown in Figures 2d-2f, this higher solutioning temperature resulted in lower average size of γ' particles after final or secondary precipitation aging comparing to those of heat treatments No.1-3. The higher temperature could more dissolve the previous coarse γ' particles into the matrix and later reprecipitated uniformly with comparatively smaller size after primary and secondary precipitate agings. Average area fractions are very similar in the range of 35-37%, as shown in Figure 3. It can be observed that when applying primary aging temperature of 1198 K and 1328 K, γ' particles after solutioning became in coarser size by particle growth process during reprecipitation like in cases of heat treatment conditions No. 2 and 3.

With solutioning temperature of 1448K in heat treatment conditions No. 7-9, as shwon in Figures 2g-2i, it was found that the average γ' particle sizes are lower than those of lower solutioning temperatures, as shown in Figure 4, due to more dissolving of previous coarse γ' particles. It can be seen that primary precipitation aging also let the previous γ' particles reprecipitating in coarser size. The average area fraction also increased with primary aging process as well as primary aging temperature. It should be noted that final microstructure after heat treatment condition No.9 has the highest area fraction (almost 45%) comparing to that of other heat treatment.

With the highest solutioning temperature of 1478 K in heat treatment conditions No.10-12, as shown in Figures 2j-2l, it was found that the average particle sizes average area fractions are very similar, as shown in Figure 3. The sizes of γ' particles in final microstructure are the finest ones comparing to those of other heat treatments with lower solutioning temperatures, as show in Figure 4. In these heat treatment conditions with highest solutioning temperature, the previous coarse γ' particles could be dissolved the most. Therefore, this resulted in very fine particle morphology. Average area fractions are about 35%.

It should be noted that hot crackings, in base metal zone near weld band, were found in weld microstructures with the highest solutioning temperature in specimens with PWHT conditions No. 10-12, as shown in Figure 5. This might be due to that the stress, occurring from very rapid γ' precipitation

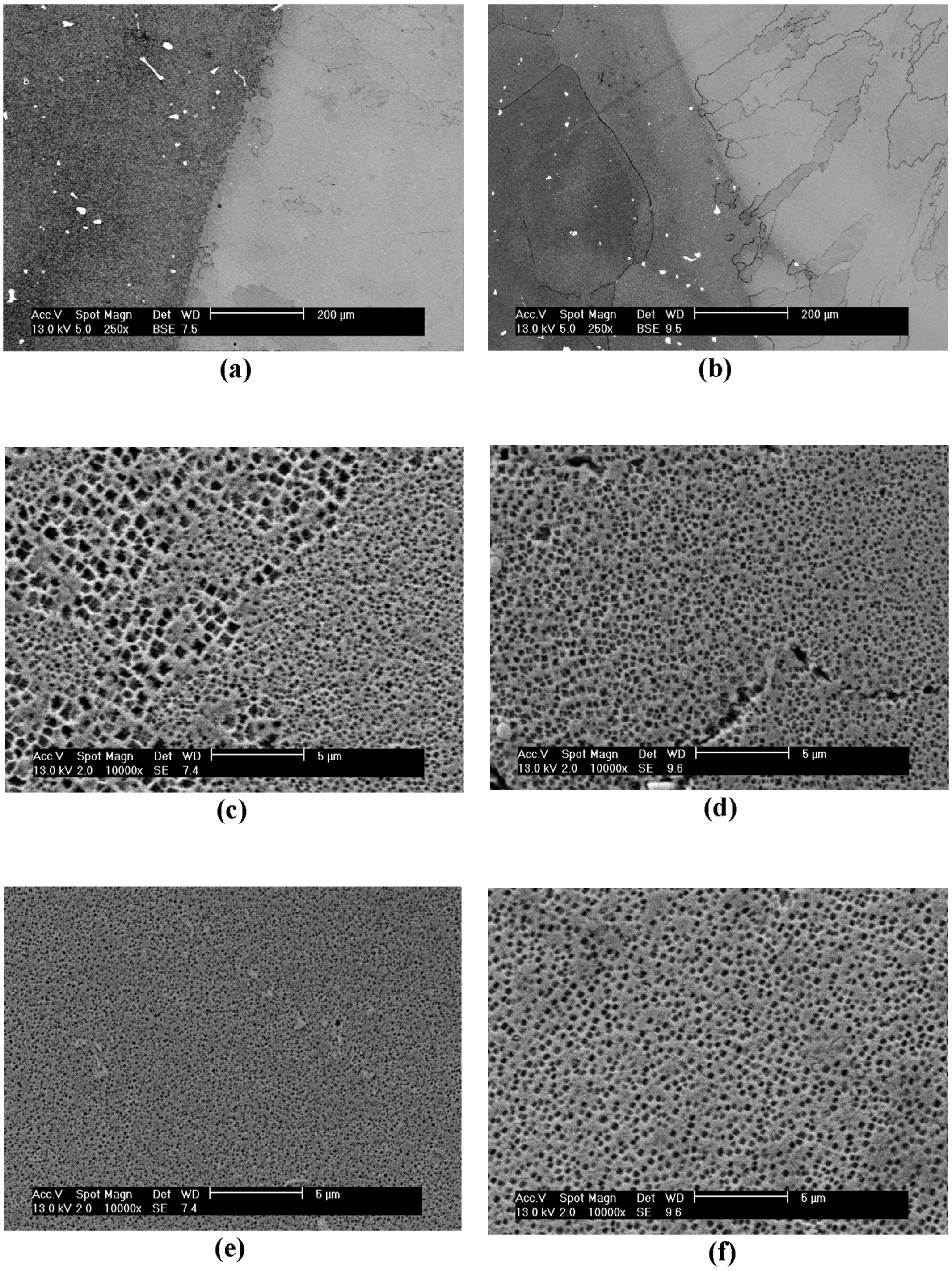


Figure 1. SEM micrographs of welded microstructures from selected samples: **a)** Weld band with PWHT condition No. 1, **b)** Weld band with PWHT condition No. 12, **c)** Weld band with PWHT condition No. 1 at higher magnification, **d)** Weld band with PWHT condition No. 12 at higher magnification, **e)** Weld filler zone near weld band with PWHT condition No. 1 and **f)** Weld filler zone near weld band with PWHT condition No. 12.

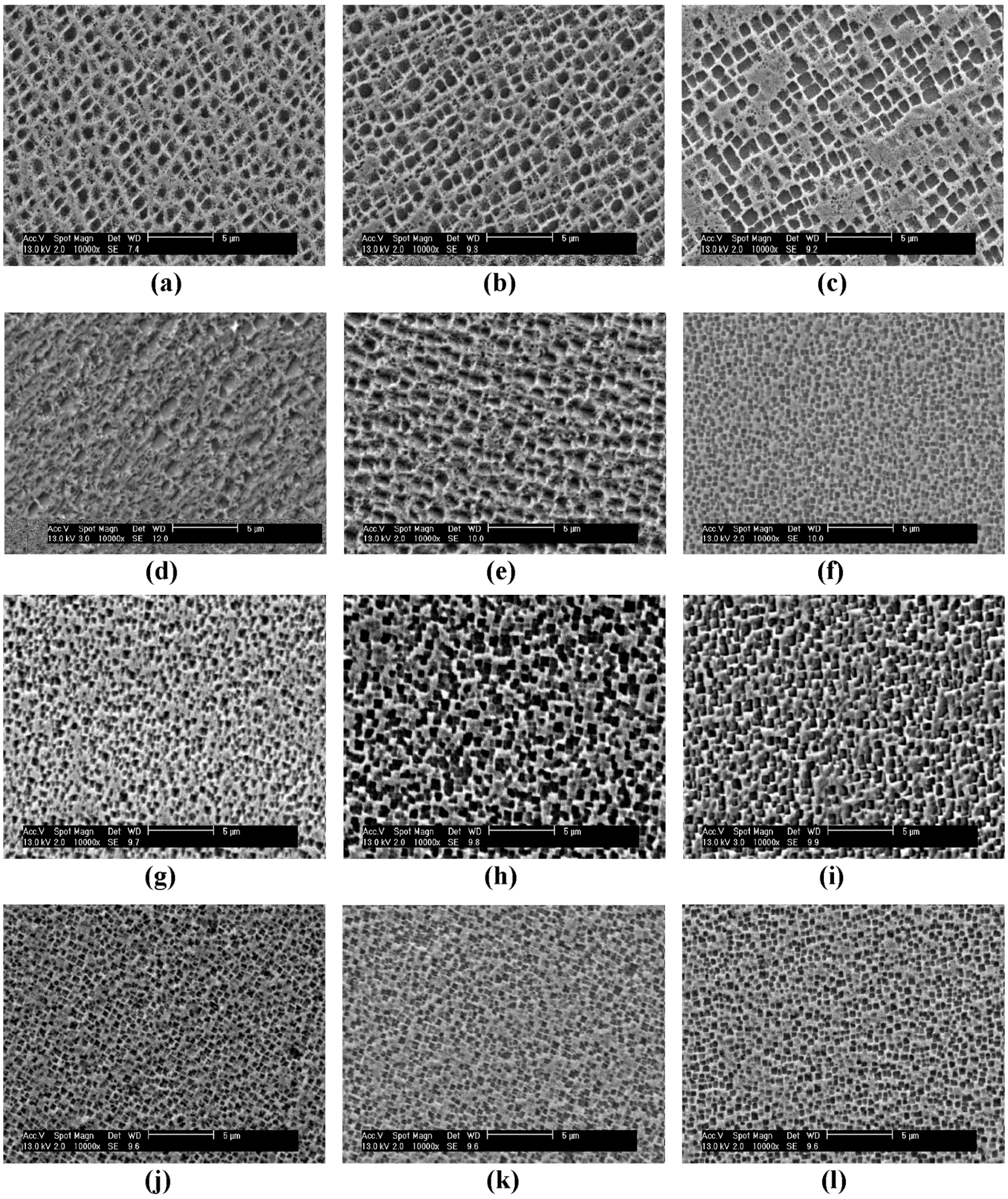


Figure 2. SEM micrographs of base metal zone of welded microstructures from samples with PWTH: **a)** Condition No. 1, **b)** Condition No. 2, **c)** Condition No. 3, **d)** Condition No. 4, **e)** Condition No. 5, **f)** Condition No. 6, **g)** Condition No. 7, **h)** Condition No. 8, **i)** Condition No. 9, **j)** Condition No. 10, **k)** Condition No. 11 and **l)** Condition No. 12.

during aging after complete solutioning, was high enough and made combination with residual welding stress. These rapid γ' precipitated particles were in very small size and densely dispersed throughout matrix in very high area fraction causing many local strain fields between γ and γ' phases.

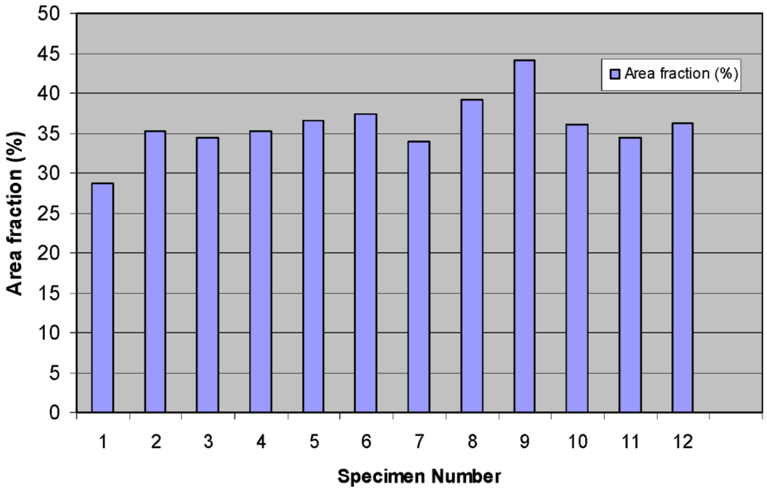
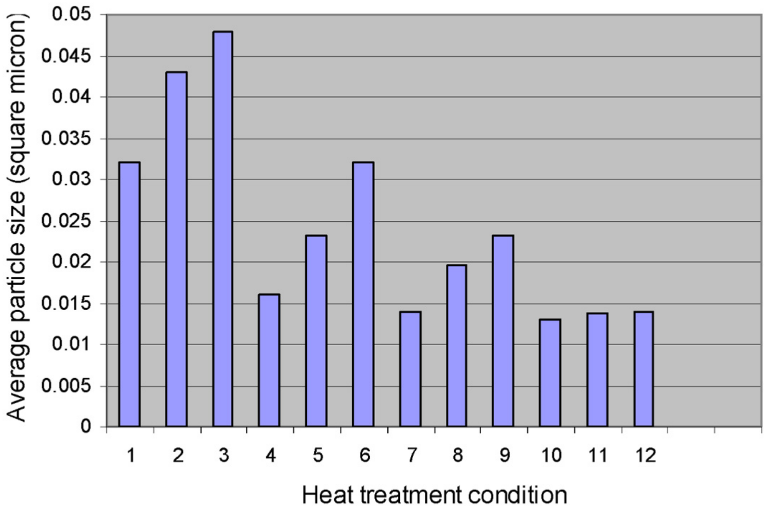
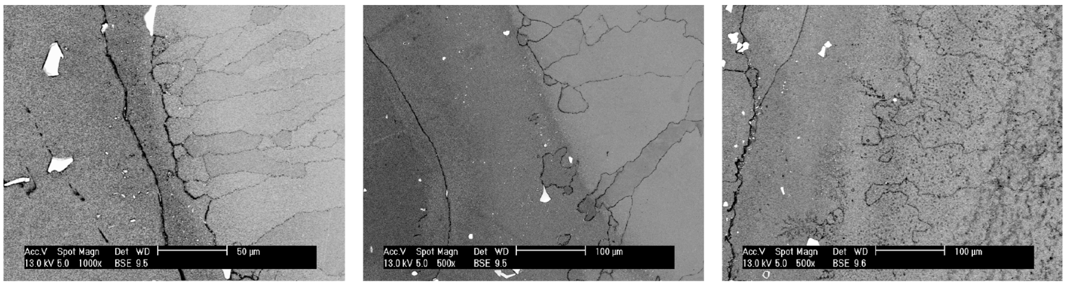


Figure 3. The relationship between are fraction and postweld heat treatment condition**.**





(a) **(b)** **(c)**

Figure 5. Cracks near weld band after heat treatment with highest solutioning temperature of **a)** Specimen No. 10, **b)** Specimen No. 11 and **c)** Specimen No. 12.

Note: IN-738 zone are in the left-side and IN-617 zone are in the right-side.

3.3 Microhardness

Figure 6 shows the results of microvickers hardness test. From the results, microhardness values of base metal are in the range of approximately 350-400. In the case of weld band areas, the microhardness values are in the range of 290-370. Generally, microhardness values of base metals are higher than that of weld zone in each heat treatment condition due to more γ' precipitation. From the hardness results, it could be summarized that the highest hardness values of the base metal and weld band are usually obtained from heat treatment conditions No. 7-12 with very high and highest solutioning temperature (1448 K and 1478 K). These high hardness values might be due to very dense of very fine γ' precipitated particles in base metal and in weld band together with more γ' particles precipitated in weld filler near the weld band. These γ' particles become coarser due to more diffusion by other elements such as aluminium and/or titanium from base metal into weld filler and then forming coarser size of γ' particles in this area.

To find out the relationships among microhardness, average γ' particles size and area fraction from Figures 3, 4 and 6, it was found that microhardness of base metal is more dependent on γ' particle sizes than their area fractions, which are not significantly different. Generally, it can be seen that the coarser γ' particle size provided the lower microhardness values. The lower solutioning temperature resulted in higher microhardness values. This can be explained that the coarser γ' particle size provided lower values of microhardness due to the different mechanism of dislocation movement.

3.4 EDX Analysis

From EDX results, as shown in Figures 7a-7c, it was found that no significant different in chemical composition was detected in filler zone, base metal and weld zone of each heat treatment condition. Elements, which were found in each zone are the same.

4. CONCLUSIONS

1. After various heat treatment conditions, it was found that the more uniform precipitation of γ' particles was clearly observed in base metal zone.

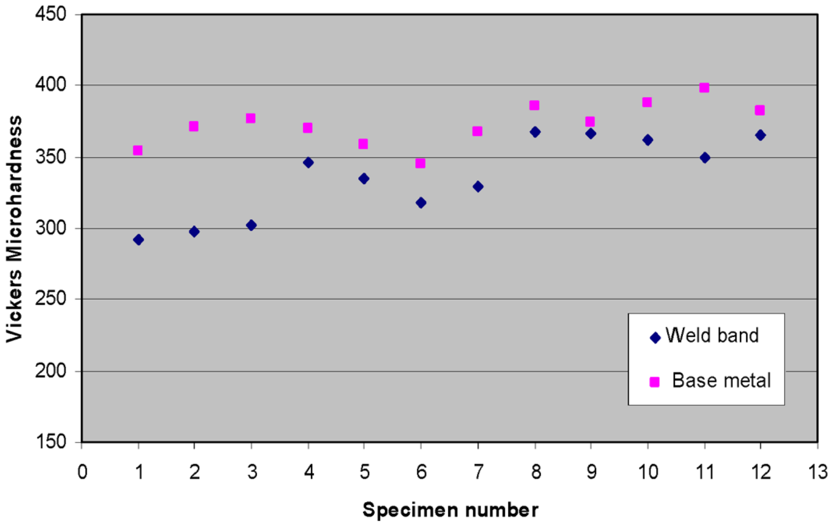
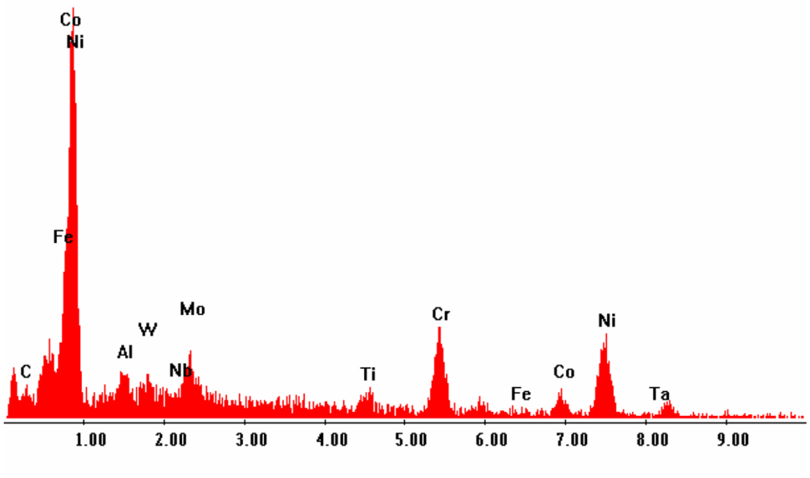
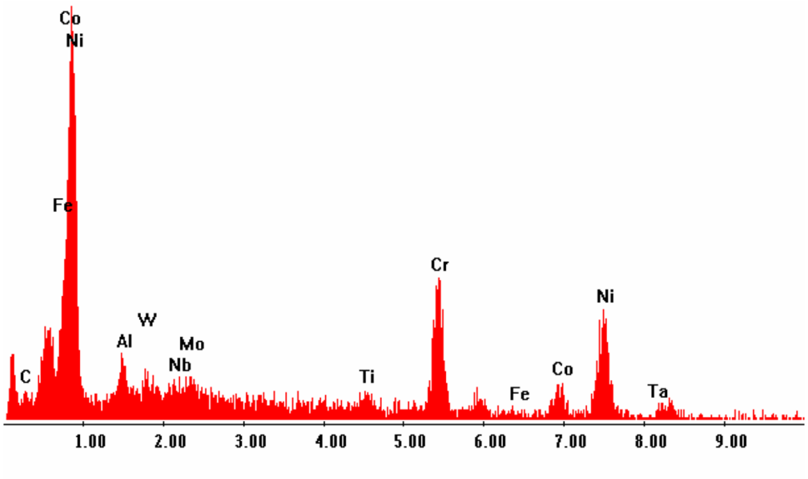


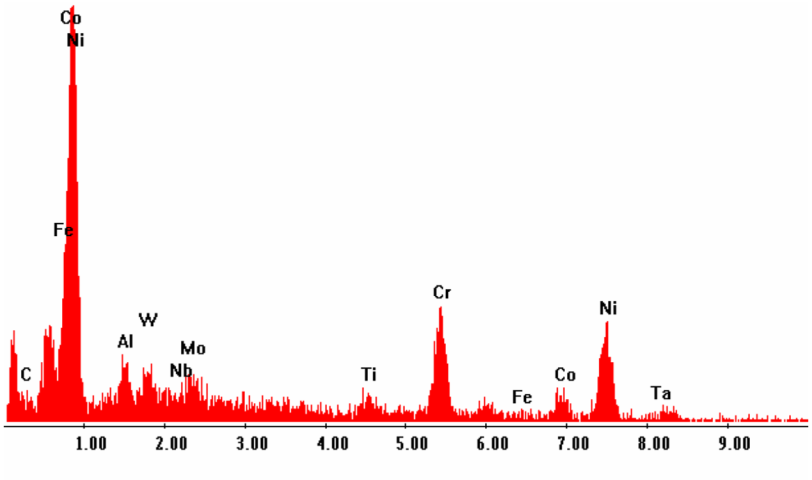
Figure 6. The relationship between microhardness and postweld heat treatment condition.



a) EDX result in filler zone



b) EDX result in base metal



c) EDX result in weld zone

Figure 7. EDX result of specimen after heat treatment condition No. 1.

2. In general, very fine γ' particles were found in HAZ in low area fraction after all heat treatment conditions.

3. The lowest solutioning temperature (1398 K) after weld process provided the most coarsening size of γ' particles in uniform dispersion in base metal zone as well as uniform dispersion of very fine γ' particles in HAZ with very high area fraction.

4. The higher solutioning temperatures after weld process resulted in smaller size of γ' particles precipitating in both HAZ and base metal zone.

5. In most cases, inserted primary aging with highest temperature (1328 K/3.6 ks (AC)) provides the slightly more coarsening of γ' particles in base metal zone but decrease the size and/or amount of very fine γ' particles.

6. The most suitable heat treatment condition after this TIG welding should be conditions No.1 – No. 3. with highest area fraction of coarse γ' particles, which might be suitable for good creep resistance.

7. The other heat treatment conditions should be proper for load conditions such as tensile and fatigue at high temperatures due to the uniform precipitation of finer γ' particles in base metal zone.

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