

# EFFECT OF PRE-POST TIG WELDING HEAT TREATMENT ON CAST NI SUPERALLOY

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## ABSTRACT

*The effect of a preheating (before) and post (after) welding heat treatment on the microstructure and mechanical properties of the scrap blades made of cast INC738LC superalloy is the main goal of the present investigation. The filler used in TIG welding was INC 625 solution hardened superalloy as proposed solution for hot cracking of the cast INC738LC superalloy in literature. The TIG welding was processed with respect to the constant optimized parameters (current, voltage, speed, gas flux rate and number of passes) to make a mechanical properties comparison between as received and the welded superalloy with heat treated specimens. The characterization techniques employed in this study are hardness measurements, tensile tests, optical microscopy and scanning electron microscopy. We found that the proposed preheating improves the TIG welding of the INC 738 LC superalloy specimens and the post welding heat treatment as expected enhances its mechanical properties.*

**KEYWORDS:** Ni-basesuperalloy; Microstructure; Heat treatment; Welding; Precipitation.

## 1. INTRODUCTION

Nickel-based superalloys typically are used most largely in the combustor and turbine sections where elevated temperatures are maintained during operation [1]. Due to the poor machinability of Ni-superalloys, one of the important manufacturing approaches widely used is vacuum investment casting [2]. Before using in service, the as-cast components are often subjected to complex heat treatments designed to establish a controlled size and distribution of precipitates [1]. They must achieve the best combination of corrosion resistance and creep strength [3] as a result of their submission to a standard heat treatment [4].

The standard heat treatment of the INC 738 LC Ni superalloy consists of a solution heat treatment for 2 hours at 1120°C air cooling+ aging treatment at 845°C for 24 h air cooling, it will produce a bimodal  $\gamma'$  (Ni<sub>3</sub>Al) precipitates [5] composed of primary cubical  $\gamma'$  precipitates and spherical secondary  $\gamma'$  precipitates. Their sizes are cited to be for the fine precipitate as 40 nm to 70 nm and coarse precipitate from 450 nm to 700 nm [6]. The hardness of the cast INC 738 LC Ni superalloy rises to a maximum value ( $H_v \approx 485$ ) at 827°C [7].

It’s recognized that during long term severe service exhibition, blades made of INC738LC Ni superalloy, undergo a series of time, temperature and stresses dependent microstructural changes as porosity, micro shrinkages and other inhomogeneities in casting parts have been reported to limit their high temperature mechanical properties [8], such as creep strength and resistance to cracking [9].

Many searchers stated that the degradation is due to the formation of secondary phases [8], i.e.; the decomposition of  $\gamma'$  precipitates (loss in volume fraction) by appearance of  $\beta$  phase [10,11] or often due to overheating and subsequently corrosion [5]. Other searchers postulated that the failure is due to the decomposition of the carbides and borides which are the grain boundaries typically strengtheners [12].

The refurbishment of the pricey components of the gas turbine blades is favoured rather than to change them, this is due to the high cost of manufacturing of the hot parts of damaged gas turbine blades used for power generation [13], especially those of turbine first stage made of the cast INC738LC Ni superalloy.

One of the economical industrial commonly used process to repair the damaged blades of a gas

turbine is the fusion welding TIG-Tungsten Inert Gas arc welding or GTAW [14]. TIG welding of the INC738LC Ni-superalloy blades without optimization of the welding parameters [15], can produce hot cracks or the grain-boundary liquation cracking due to the boron segregation [13].

Many studies report that the solution to the hot cracking mechanism during welding of the Ni superalloy and post-welding heat treatment is avoided by suitable and practical preheating [16, 8]. It was mentioned also that a preheating at 1055°C can make the material ductile, with hardness about of 340 Hv, avoiding forming of cracks after TIG welding [7, 8], others stand the use of a solution hardened superalloy as INC 625 [17]. The thermal cycles during welding of the Ni-base superalloy can promote decreasing of the mechanical properties of the welded joint [18].

Finally, after the TIG welding; the joined parts of the INC 738 LC Ni superalloy were subjected to post-welding heat treatment, its ultimate goal is to obtain a Ni superalloy with important mechanical properties [19] and to improve material service life [20].

From the analysis of nowadays literature, there is no much research relating the mechanical properties of the cast Ni-base superalloy joints, using optimized parameters of TIG welding process and combined thermal regime (preheating and post-weld heat treatments).

## 2. EXPERIMENTAL

The Ni-base super-alloy used in this study was a trade mark INC738LC, with low carbon content. The sample was provided in as cast state, from a blade of first stage gas turbine of Electric Power Plant of M'sila, Algeria. The analysed blade has been in service for about 64,000 h. Table 1 presents the nominal composition of as received base material.

The shape of the INC738LC superalloy plates is shown in figure 1. The samples were cut from a gas turbine blade (MS9001-1st stage), from the root cooling zone, using a wire-discharge cutting machine (EDM "AF 35"), in laboratory of Maintenance of Industrial Equipment's MIE company, Algeria [21].

**Table 1.** Nominal composition of the Ni based superalloy material used [15]

Element	Wt%
Al	3.65
Nb	0.86
Mo	1.74
Ti	3.08
Cr	15.40
Fe	0.23
Co	8.20
Ta	1.39
W	2.95
Ni	Bal.



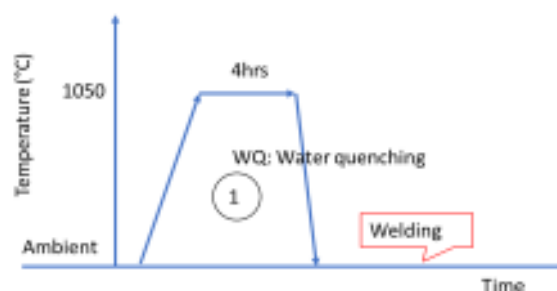
**Fig. 1.** The plates cut from the blade root of the Ni superalloy INC738LC with 2 mm thick

### 2.1 Microhardness Measurement

The microhardness of as received INC738LC base material has been measured using microhardness apparatus (LECO M-400-A hardness tester) and an indentation force value of 5 N for 15 seconds. The mean value of microhardness, obtained in 10 different measuring points, was 398.17 HV. The application of the preheating is considered mandatory.

### 2.2 Preheating

Before welding the plates were subjected to a proposed preheating, as presented in figure 2. It consists of primary precipitation treatment (at 1055°C/4 hrs/WQ “water quench”) which may lead to regenerate the carbides and borides, giving some ductility to the superalloy. This preheating was inspired from the heat treatment applied by Danis & al. [22] and Xu & al. [8]. The proposed preheating cycle improves in time efficiency compared to the time made for the preheating cycles of the U.M.T “University of Manitoba Heat treatment” by decreasing to 66.67 %, to 77% for the NUMT “New U.M.T” and to 62.5 % for the FUMT “Furnace U.M.T” [23], making a save in the amount of the heat energy needed for preheating.



**Fig. 2.** The proposed diagram of preheating

Before the TIG welding process, plates were chamfered and a deep V groove of 35° angle was machined.

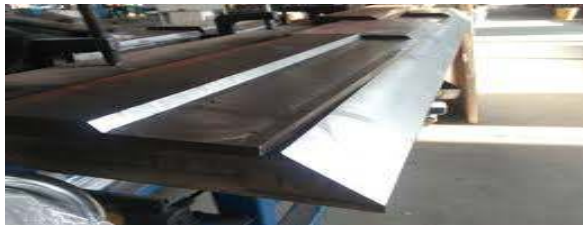


Fig. 3. Plates chamfered

### 2.3 Post-welding Heat Treatment

After welding, Post weld heat treatment (PWHT) is essential to improve the homogeneous microstructure and mechanical properties in weld zone” [20]. For that the welded parts were subsequently subjected to post-welding heat treatment as shown in figure 5, which has been defined by Wangyao& al. [19].

### 2.4 Welding Process

For the TIG welding process has been used a Miller Syncrowave 350 L apparatus (XMT 450 CC/CV). The values of optimized welding parameters (that were kept quite constants) are reported in table 2. Before welding the joining surfaces were slightly with sandpaper P240 and cleaned with acetone. The welded joint obtained is shown in figure 4.



Fig. 4. The welded specimens

Table 2. TIG welding parametrs

TIG welding apparatus	Millersyncrowave 350 L × (XMT 450 CC/CV)
Welding speed (mm/s)	0.4
Argon gas rate flow (l/min)	8
Number of passes	2
Welding current (A)	40
Welding voltage (V)	10
Filler used INC 625 Ø (mm)	1.6
Deep V groove angle (°)	35
Space (distance) between Ni superalloy plates (mm)	2

The INC625 filler was selected as suggested by Banerjee & al. [17], its chemical composition is shown in table 3.

Table 3. Chemical composition of the INC625 filler

Element	Wt%
Al	0.40
Nb	3.31
Mo	8.39
Cr	20.95
Fe	0.27
Co	1.00
Ti	0.13
Ta	2.74
Ni	Bal.

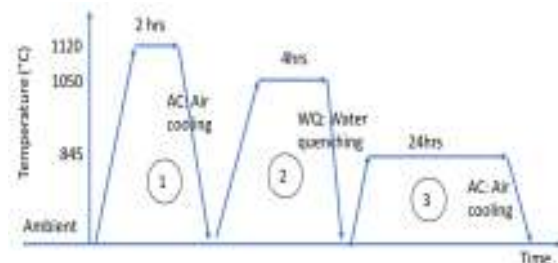


Fig. 5. The diagram of post-welding heat treatment

## 2.5 Machining Tensile Test Specimens

The tensile test specimens were cutting from the welded plates after post-welding heat treatment by use of the numerically controlled wire discharge machine (EDM"AF 35"). Figure 6 presents the shape and the measurements of the tensile experimental specimen. The welded zone is in the middle of the tensile-test specimens.

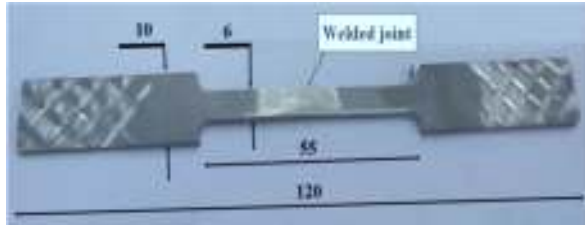


Fig. 6. The tensile test specimen

## 2.6 Metallurgical and Mechanical Characterizations of Welds

### 2.6.1 Metallographic Characterization

The metallographic observations of the base metal structure, welded and heat-treated parts are carried out using the computer-assisted "Leica Microsystems Belgium BVBA-DMLM" type microscope. The surface examination of the sample was possible with applying (Marble's reagent) for 30 seconds as dwell time. The average volume fraction or population of coarse  $\gamma'$  particles was determined by the surface area measurement using "image J" software.

### 2.6.2 Mechanical Characterizations

The as received metal and the pre-post welding heat treated plates were subjected to the mechanical tests (microhardness measurements, tensile tests). The hardness of the pre-welding metal was taken in mean value (10 measurements). The hardness of the welded and post-welded heat-treated joints was quantified with a space of 0.5 mm from the base metal to the welded zones. The three specimens of INC738LC Ni superalloy as received and the three-welding heat treated specimens were also subjected to tensile tests by using a Zwick/RoellZ100 tensile experimental machine at a constant speed of 2 mm/min as cited by Saib and Boumerzoug[15].

### 2.6.3 Fracture Faces SEM Observations

The cross-section observations of broken specimens after tensile tests were realized by Scanning Electron Microscopy (SEM) TESCAN VEGA Easy Probe.

## 3. RESULTS AND DISCUSSION

### 3.1 Microstructure Observations

#### 3.1.1 Microstructure of the as-received Metal

The as-received INC738LC superalloy was obtained from a blade, which had been operating in gas turbine engine at high temperature for several years. Figure 7 shows the base metal microstructure. A dendritic structure is observed which indicates that the blade was produced by conventional casting process. We observe that the alloy has a multi-phase microstructure composed of FCC  $\gamma$  austenitic matrix, bi-modal  $\gamma'$   $\text{Ni}_3(\text{Ti},\text{Al})$  intermetallic precipitates (primary "coarse" and secondary "fine"),  $\gamma$ - $\gamma'$  eutectic, carbides [20]. The coarse  $\gamma'$  precipitates had a 34 % as volume fraction.

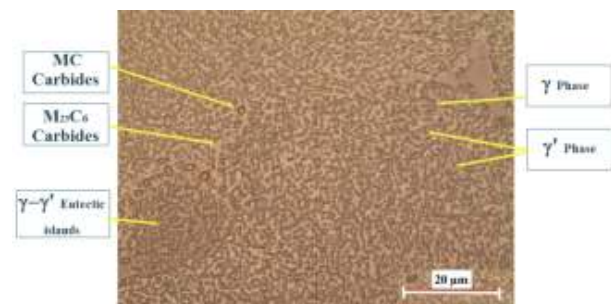


Fig. 7. Microstructure of the as-received metal

#### 3.1.2 Microstructure of the Preheating Ni Super alloy

##### 3.1.2.1 Microstructure of the INC738LC After the Primary Precipitation Heat Treatment (1055°C/4h/WQ)

Figure 8 shows the microstructure of the INC738LC Ni superalloy after isothermal heat treatment at 1055°C which is called the primary precipitation. The outputted of volume fraction of coarse  $\gamma'$  precipitates increased to 23%. A segregation between the grains is observed, with the existence of a large fraction of blocky MC carbides (in grain boundary and intergranular). The shape of grain boundaries has a continuous and finer form which is the suitable shape to weld the superalloy without cracks as mentioned by Thakur [7].

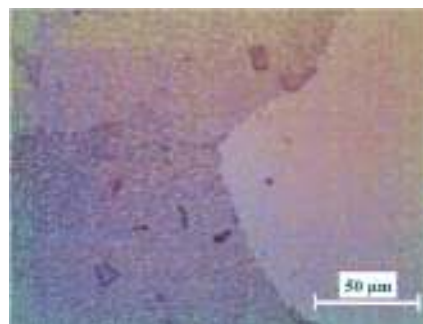


Fig. 8. Microstructure of the INC738LC Ni superalloy after primary precipitation heat treatment

### 3.1.3 Microstructure of the Welded Ni Superalloy

Figure 9 represents the different zones of the INC738LC Ni superalloy microstructure welded joint. The welded joint microstructure differs significantly from the parent metal [24].

We observed a segregation in the microstructure of the base metal between the grains, one with fine  $\gamma'$  precipitates and other with bimodal  $\gamma'$  precipitates, with 24% as volume fraction of coarse  $\gamma'$  precipitates, in addition the presence of different carbides, borides, these constituents were continued in the HAZ at the base metal side. Laves phases are rejected to the interface between FZ and HAZ. In FZ, we detect the

$\gamma''$  precipitation and the appearance of the  $\delta$  phase, small amount of the  $\gamma'$  precipitation and Laves phase had the bulk appearance as the MC carbides.

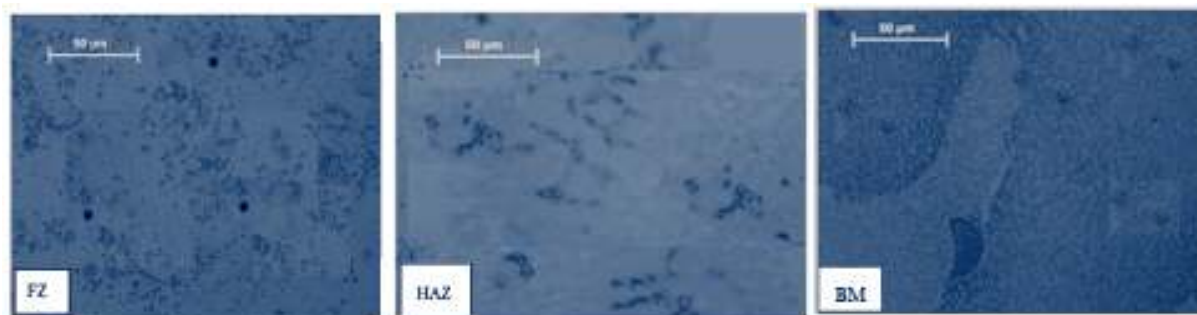


Fig. 9. Microstructures in the (BM, HAZ, FZ) of INC738LC Ni superalloy after welding.

### 3.1.4 Microstructure of the Post-welding Heat Treated Ni Superalloy

Figure 10 shows the different zones of the welded joint microstructure after post-welding heat treatment of the INC738LC Ni superalloy. We noticed that near the base metal, the presence of the coarse  $\gamma'$  precipitates where their volume fraction was 44%. In the FZ side, very fine  $\gamma'$  precipitates exist. However, the difference in  $\gamma'$  precipitates size between coarse and very fine is due to the forming atoms of  $\gamma'$  precipitates which could

diffuse in more amount and/or more far distance from the base metal zone to FZ after complete dissolution of all  $\gamma'$  precipitates during higher temperature of (re) solution treatment and finally re-precipitate in uniform size after aging heat treatment as described by Wangyao & al. [19].



Fig. 10. The microstructures in the (BM, HAZ, FZ) of INC738LC Ni superalloy after post-welding heat treatment

## 3.2 Mechanical Characterization of INC738LC Ni Superalloy

### 3.2.1 Microhardness Measurements

#### 3.2.1.1 The as-received cast INC738LC Ni Superalloy and the filler

The mean microhardness value (10 measurements) of the base metal Ni superalloy INC 738 LC as received was: 398.17 Hv. On the other hand, the mean microhardness of the INC625 filler metal was evaluated to have as value of 256.41 Hv.

#### 3.2.1.2 The Preheating of the INC738LC Ni Superalloy

The average microhardness of the Ni superalloy after primary precipitation heat treatment (4 hours at 1055 °C/WQ), reached the value of 350, 24 Hv. The hardness of the metal decreases when the  $\gamma'$  coarser increases a little in volume fraction versus to the fine  $\gamma'$  precipitates.

#### 3.2.1.3 The welded INC 738 LC Ni Superalloy

The values of the mean microhardness measured on the different zones of the welded joint are represented with thick blue line in figure 11.

- After welding, high hardness values were obtained in the heat affected zone (HAZ) about 500,01 Hv, in FZ we registered 369,83 Hv as hardness and about 350, 24Hv in base metal.

#### 3.2.1.4 The Post-welding Heat Treated INC 738 LC Ni Superalloy

The values of the mean microhardness measured on the different zones of the welded bead after the different cycles of heat treatment post-welding are represented by thin brown, thin green and thick red lines in figure 11.

-After welding followed by the (re) solution (quenching) and (re) precipitation treatment, the microhardness of the base metal was in order of 415,56 Hv whereas the HAZ approached to 499,74Hv, while that of the FZ was equal to 450,32Hv. This minor raise in hardness is due to the (re)precipitation of the strengthening phases  $\gamma'$ ,  $\gamma''$ ,  $\delta$ .

It has been found that in the FZ, the precipitation of  $\delta$ ,  $\gamma''$  increases the yield strength. The high hardness values might be also due to very dense of very fine  $\gamma'$  precipitates in base metal and in HAZ together with more  $\gamma'$  precipitates in weld filler near the HAZ [25]. It has been found that these  $\gamma'$  precipitates become coarser due to more dispersion by other elements such as aluminium and/or titanium from base metal into FZ and then forming coarser size of  $\gamma'$  precipitates in this area [26].

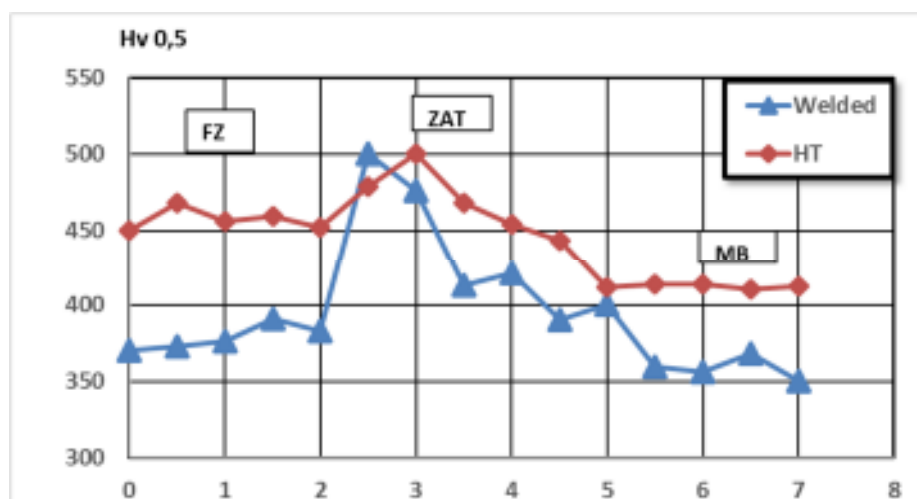


Fig. 11. Micro hardness measurements after welding and post-welding thermal cycles

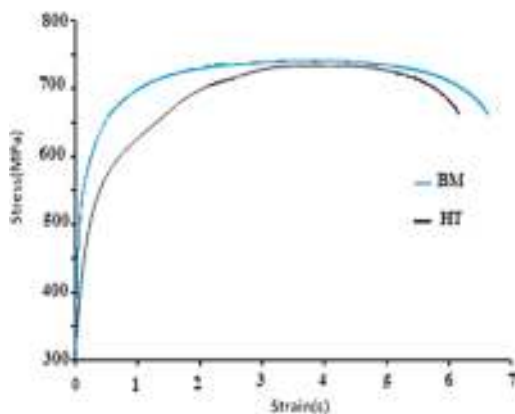
### 3.2.2 Tensile experimental

Tensile experiments were carried out at room temperature 20 °C on base metal (as received) specimens and on heat treated welded specimens

(figure14), thus allowing to make a comparison of their mechanical characteristics. The tensile tests results are shown in figure 11 and table 4.

Figure 12 shows the tensile curves where we noticed that the tensile curves of the specimens consist of the

following conventional zones: an elastic zone followed by a plastic zone and finally the rupture. The higher mechanical strength (UTS) is realized in the base metal specimens followed by the heat treated post-welded specimens respectively. The ultimate tensile strength of the heat-treated welded specimens was similar to the as received metal ( $718.47\text{MPa} \approx 721.21\text{MPa}$ ). The ultimate tensile strength of the heat-treated welded specimens was greater by ( $67.41\text{N/mm}^2 \approx 70\text{MPa}$ ) and the Young's module by  $42\text{GPa}$  respectively compared to the welded specimens with the optimized TIG welding parameters without undergone any post heat treatment as reported by Saib and Boumerzoug[15].

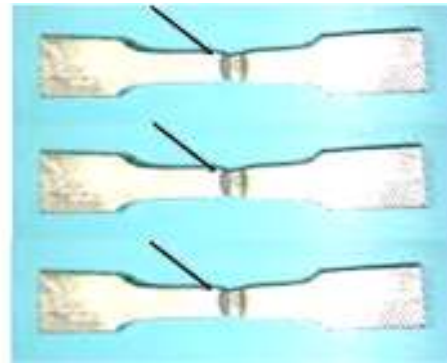


**Fig.12.** Tensile curves of the post-welded heat-treated specimens (HT) versus the base metal (as-received)

**Table 4.** UTS results.

Specimens	UTS (N/mm <sup>2</sup> )	E(GPa)
Cast reference [8]	765	200
BM (Base metal-as-received)	721.21	191
WOP (welded with optimized parameters) [16]	651,06	134
HT (Welded Heat Treated)	718.47	178

Figure 13 shows that the broken welded heat-treated specimens after tensile tests, they were fractured in the FZ very close to the HAZ.



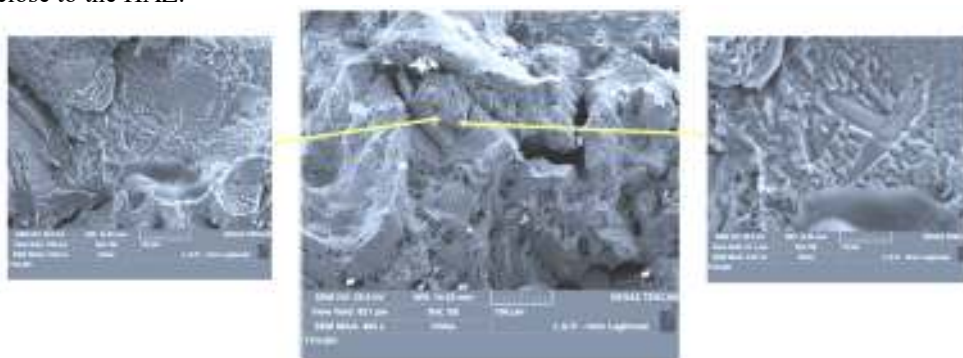
**Fig. 13.** The broken post-welding heat treated specimens after tensile test

### 3.2.3 Fractography

SEM observations were performed to analyse the nature of fracture faces for weld seams after tensile experiments of the base metal (as received) specimens and the welding specimens with different thermal cycles, to relate the fracture characteristics with structure and properties. The fractured surfaces of broken specimens of the base metal showed the cleavage fracture [27].

In the fractured heat treated post-welded specimens shown in figure 14, the structure consists of grain boundary voids produced during plastic deformation. The voids are coalesced and made grain boundary cracks. The fine dimples present on the fracture surface indicating void coalescence and ductile intergranular fracture [28].

The white precipitates are primary MC carbides distributed along the interdendritic regions and grain boundaries [27].



**Fig. 14.** SEM observations of a fracture faces of the specimen post-welding heat treated Ni superalloy

#### 4. CONCLUSIONS

Through this investigation, the structural and mechanical properties of the welding of the INC 738LC superalloy with pre-post welding heat treatments were explored; the results can be shortened as follows:

- The hardness of the as-received cast INC738 LC Ni superalloy was 398.17 Hv and the coarse $\gamma$ ' precipitates volume fraction was about 34 %.
- The preheating of the cast INC 738 LC Ni superalloy lets its hardness decreases to a low value about 350.24, however the volume fraction was 23% as volume fraction of coarse $\gamma$ ' precipitates.
- During welding; when the cast Ni superalloy (base metal) is exposed to high temperature of the TIG welding torch, in the HAZ at the base metal side lets the hardness of the welded Ni superalloy to change from 350.24Hv to 500,01Hv, but the volume fraction of coarse $\gamma$ ' precipitates in the base metal was 24%. In the FZ, the hardness was 369,83Hv.
- The hardness of the post-welded heat-treated cast Ni superalloy (base metal) increases to reach the value of 415,56Hv, 44% is the volume fraction of coarse $\gamma$ ' precipitates. In the FZ, the hardness jumps to 450,32Hv.
- The ultimate tensile strength and Young's module of the heat-treated welded specimens were similar to those of as received metal.
- The welding of INC738 LC Ni superalloy free of cracks needs preheating and post heat treatments to improve the blades mechanical properties and life service, this layout may be used to repair the scrap turbine blades.

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