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Abstract - Inconels 792 are nickel-base superalloy material that has high strength and creep resistance at temperature near their melting point. This material is commonly used in aircraft gas turbine (jet) engines, where parts or components are subjected to high temperature and high stress. Notwithstanding the high-temperature capabilities of the alloys, during service the parts are often damaged by hot gas erosion and other types of mechanism. Welding is one of the repair method available nowadays. The application is typically accomplished by Gas Tungsten Arc Welding (GTAW). Unfortunately, however, these superalloys also have limited ductilities at elevated temperatures, and are consequently subject to cracking due to differential thermal strains in some temperature ranges, a phenomenon termed "strain-age" cracking. The solution proposed is Superalloy Welding at Elevated Temperature (SWET). Elevating temperature on the parts or components that are to be welded probably could reduce the thermal gradient occurred, thus creating a crack-free weldments. Also elevated temperature could reduce the amperage needed to achieve the welding temperature, hence lower electricity and cost are resulted.

Keywords : Inconel, Superalloy, GTAW, SWET.

I. Introduction

Nickel-base superalloys are extensively used in aircraft gas turbine (jet) engines. These superalloys which have the highest volume of precipitates, typically 40 volume percent or more, exhibit the highest strengths and creep resistances at temperature near their melting points (Flowers, G.E, at al.1998).

These high-volume-fraction gamma prime superalloys are used in articles such as turbine blades and vanes, which operate at high temperature for prolonged periods. Hence, these parts are often damaged by hot gas erosion and other types of mechanisms. However, these superalloy materials are difficult and expensive to manufacture. Therefore, when such parts or components are damaged during engine operation, it is far more desirable to repair rather than replace it. As a result, a variety of repair method have been developed and reported.

Repair of damaged region is commonly accomplished by a welding process. After the damaged area is cleaned, a filler metal is melted and applied to the damaged area. The application is typically accomplished by tungsten inert gas welding, wherein an electric arc is struck between the article and a tungsten electrode, forming a molten pool in the damaged region. But there is a problem with the precipitation hardenable alloys, such as Inconel 792. These materials have the inability to weld with a like material for purposes of repair. Welding initiates high temperatures that have a tendency to cause cracking at the area of the weld site, thereby resulting in destruction of the welded parts. The biggest issue is the creation of differential thermal stresses that lead to strain-age cracking and liquation cracking in the weldment and in adjacent regions of the welded substrate. This cracking is harmful to the performance of the welded parts, and a number of methods have been proposed to overcome the cracking.

In one such approach, the application of Superalloy Welding at Elevated Temperature (SWET) is conducted on the parts. Pre-heating prior to welding is done to a temperature greater than its aging temperature and to maintain that temperature during the welding operation. Generally, the purpose of SWET is to minimize the thermal gradient, thus reducing the residual stress created on the weldment. This article will describe the SWET technique and the advantages of its application. An experiment has been carried out to see the performance of the application and will also be explained.

II. What is SWET

Superalloy, like it has been mentioned before, is a very difficult-to-weld material. SWET is advancement in repairing or welding cast superalloy. The application process is heating the article to elevated temperature and maintaining that temperature prior to welding. In the application of SWET, preheating should be in a temperature greater of its aging temperature. This is to avoid the precipitation phase to commence resulting strengthening of the material. The combination of strengthening and stress produced by the welding can cause cracking (Everett, M.A., 1987)

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Preheating will also reduce thermal gradients due to welding operation. Under rapid heating, the grain boundary phases are unable to dissolve fully into the surrounding matrix and partial dissolution leads to the formation of a low melting point eutectic and melting of the grain boundary region. Local dissolution of grain boundary phase will cause liquation cracking or fissuring. Preheating will also reduce cooling rate, thus producing more ductile metallurgical structure with greater resistance to cracking. For superalloy material, preheating typically carried out ranging from 500°C – 1010°C [Mokadem, S. , 2009).

III. Welding Defect

The major difficulty of welding a superalloy is the occurrence chance of defects on the weldments (Fig.1). Most common defect is the hot cracking. Hot cracking predominantly occurs in the Heat Affected Zone (HAZ). Hot cracking occurs due to the effects of the thermal cycle of welding. Rapid heating and cooling occur in the area adjacent to the weld. Incipient melting can be caused by the welding process. Incipient melting at grain boundaries can lead to reduced ductility and subsequent cracking (Donachie, M.J. & Donachie, S.J., 2002).

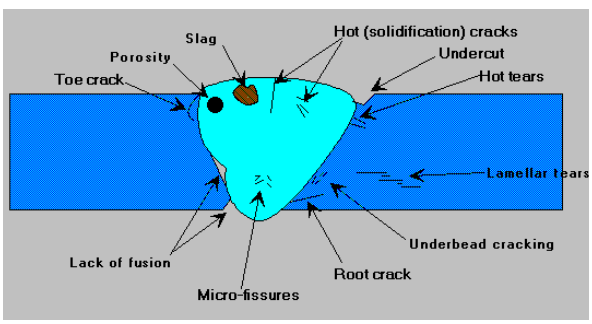

Fig. 1 : Types of defects on weldments (Fontana, F.G., 1987)

Liquation cracking in the HAZ is also another defect that can form due to welding. The liquation or melting occurs because of a reaction between dissolving precipitate and the matrix. When melting is accompanied by sufficient thermal stress, fissuring can form along the HAZ grain boundaries and extend into the fusion zone.

IV. Experiment Procedures

a) *Inconel 792*

Inconel 792 is classified in as-cast nickel-based superalloy which is used for components operating in high temperature, corrosive environment with high working load. This material is typically used for turbine wheel APU that has working temperature ranging from 566 °C – 650 °C and rotating speed at 41.700 RPM (Unknown, 2003). Inconel material exhibit high strength and creep resistance at temperature below their melting points. However, these superalloys also have limited ductility at elevated temperature.

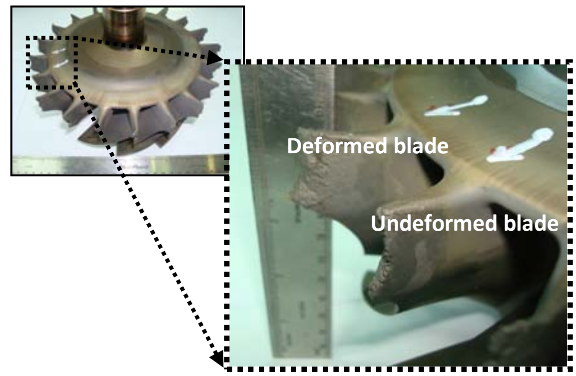

Fig. 2 : Failed and worn out turbine wheel blade tip due to cracking, two samples of defomed and undeformed blade were researched

For the experiment, composition analysis on the specimen is conducted by Energy-Dispersive X-ray analysis (EDX) method.

Tabel 1 : Measured on the spot by EDX system analysis compared to the standard of Inconel 792

Chemical Element	IN-792 (%) Std	Measured on Base
C	0.2	1.7
Ni	60	67.56
Cr	13	10.91
Co	9	11.69
Mo	2	-
Fe	-	-
Al	3.2	2.45
B	0.02	-
Ti	4.2	3.99
Ta	-	-
W	4	-
Zr	0.1	-
Other	2 Nb	1.13 Si
		0.57 S

b) *Preheating*

For this experimental purpose, preheating is applied on temperature 200 °C, 400 °C and 600 °C for 1-2 hours. Preheating the article is performed using a heater and a larger mass holder, as shown in Fig.3.

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Fig. 3 : Photograph of larger mass holder covered with heater, part marked as red circle

c) Repair Welding

Most common arc welding technique used in many industries is the Gas Tungsten Arc Welding (GTAW). GTAW is a welding process that uses an arc between a tungsten electrode (non-consumable) and the weld pool. The process is used with shielding gas and without the application of pressure. The process may be used with or without the addition of filler metal.

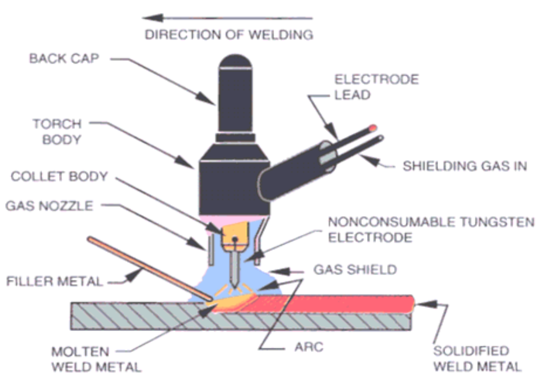

Fig. 4 : Schematic of GTAW Technique (http://www.spectroweldinstitute.com)

GTAW has become indispensable as a tool because of the high-quality welds produced and low equipment costs. GTAW can be used to weld more materials than any other welding process, even exotic and heavier-alloyed metals. Among those materials you can successfully use GTAW for stainless steel, aluminum, nickel, and titanium. This has become the main reasons for selecting GTAW on the repair application (Fig.4).

d) Advantages of GTAW Technique

- Produces superior quality of welds, generally free of defects.
- Free of the spatter which occurs with other arc welding processes.
- Can be used with or without filler metal as required for the specific application.
- Allows excellent control of root pass weld penetration.
- Produce inexpensive autogenously welds at high speeds.
- Can use relatively inexpensive power supplies.
- Allows precise control of the welding variables.
- Can be used to weld almost all metals, including dissimilar metal joints.
- Allows the heat source and filler metal additions to be controlled independently.
- Allows for welding in all positions.

e) Process

After the article has been mounted on to the larger mass holder and preheated, the welding process can be performed. The GTAW process uses a non-consumable tungsten (or tungsten alloy) electrode held in a torch. Shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal from contamination by the atmosphere (Unknown, 2008).

The electric arc is produced by the passage of current through the conductive, ionized shielding gas. The arc is established between the tip of the electrode and the work. The electricity used for this process is fed from a 65 KVA 3 Phase 63 Ampere 50 Hz Power Electric (Fig.5). Heat generated by the arc melts the base metal. Once the arc and weld pool are established, the torch is moved along area being repaired and the arc progressively melts the faying surfaces. Filler wire, if used, is usually added to the leading edge of the weld pool to fill the repaired area. Cooling of this process is then conducted by still air.

Fig. 5 : GTAW process being performed

V. Repair Results And Discuss

As shown in Fig.6, the welding process has been initiated without any trouble. Visual inspection has been conducted to see any defects on the welded surface and also the HAZ. Observation reveals there is no defect detected yet. Further examination on microstructures should be initiated to see any defects occur in the subsurface.

Fig. 6 : Photographs of welded articles, weldments are marked with red circle

Noticed during the repair accomplishment, the increasing preheating temperature on the parts reduces the amperage needed to achieve the arc of welding. Lower amperage will reduce electricity usage, hence lower cost is needed for welding application. Electricity usage was noted and shown in Table 2.

Table 2 : Electricity usage during welding operation

	Temperature (°C)	Voltage(V)	Amperage (A)
I.200	200	10	17
I.400	400	10	13
I.600	600	10	11

a) Metallographic Examination

Fig. 7 : Photographs of prepared specimen for metallographic examination

Fig.7 shows metallographic practice by cutting, sectioning, mounting, grinding, polishing, and etching was done per ASTM E 3 & E 407. The etching reagent used in this practice was Kalling reagent's No. 2.

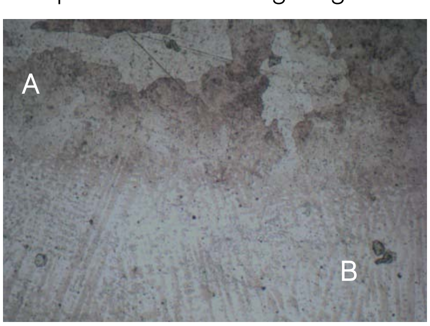

Fig. 8 : Stereo-microscope Photograph of SWET application on 400 °C, A) Base metal and B) Weld metal, etched by Kalling Reagent's no. 2, 100x

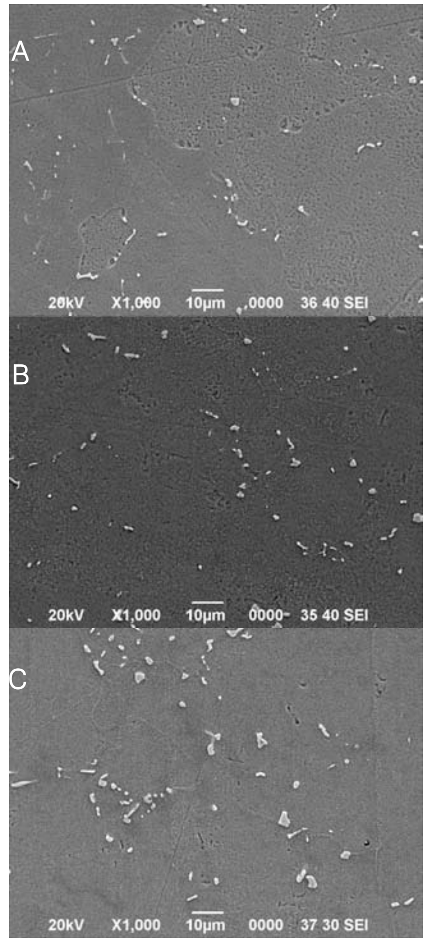

Fig. 9 : Photograph of SEM result welded specimen heated at A) 200 °C, B) 400°C and C) 600°C, Etched by Kalling Reagent's no. 2, 1000x

It is shown on Fig.8, distinct material difference between base metal, Inconel 792, and weld metal, Inconel 625, separated by diffusion line.

Fig.9 shows SEM results after been etched. On the entire specimens, it can be seen carbides forming on the grain boundaries. Gamma-prime precipitates are also available within the gamma matrix. Different color on photographs as an effect of different contrast applied during SEM.

Fig.10 shows photographs of the base metal and weld metal microstructure. Photographs are taken using SEM with 1000x magnification. Fig.10A, 10C and 10E shows base metal with different preheating temperature applied, in orderly 200°C, 400°C, and 600°C. Increased preheating temperature results increasing maximum cooling rate. Hence, softer and smaller grain sizes are formed on the metal. Reducing grain size reduced susceptibility to hot cracking (Donachie, M.J. & Donachie, S.J., 2002). However, there is no distinct difference between the base metal.

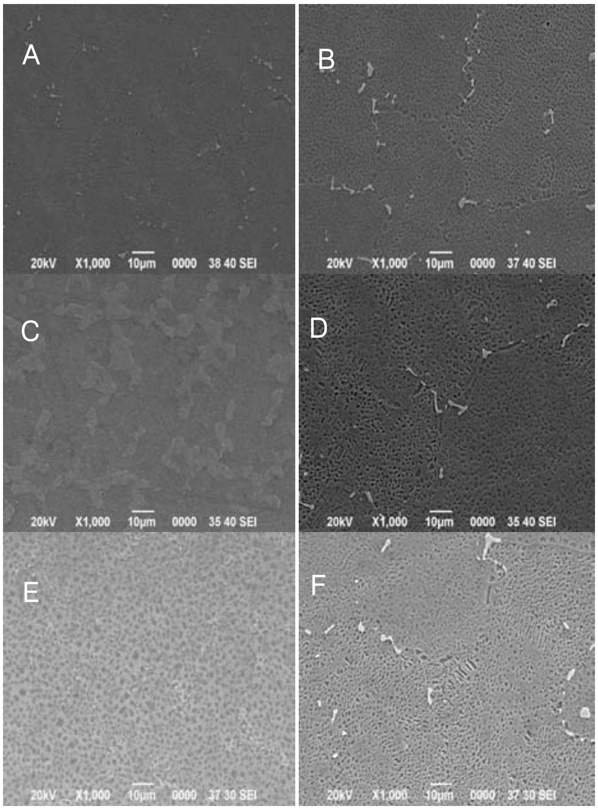

Fig. 10 : Photograph of weld metal and base metal under SEM metallography, 1000X

Fig.10B, 10D and 10F shows no microstructure changes. Because the base metal is far from the welding area and preheating temperature are kept below phase transition temperature, no changes occurred (Unknown, 1992).

As seen on Fig.11, microcracks have been detected on the article that was welded at temperatur 200 °C. Based on the location of the cracks which is on the HAZ area, it is predicted as a liquation cracking (Donachie, M.J. & Donachie, S.J., 2002). Rapid heating on the article creating a huge thermal gradient resulting thermal stress around HAZ area. Another stress applied on the area came from the welding procedure. Welding direction creates transversal tension on the specimen, adding up more stress. The present of a second-phase precipitate can cause increased hardness of the specimen. Increasing hardness and the inability to relieve stress due to welding are a perfect combination to cracking. Increased preheating temperature prior to welding is proposed to reduce thermal gradient and increase maximum cooling rate which enable the article to relieve thermal stress (Haafkens, M.H.,& Matthey, J.H.G., 1982)

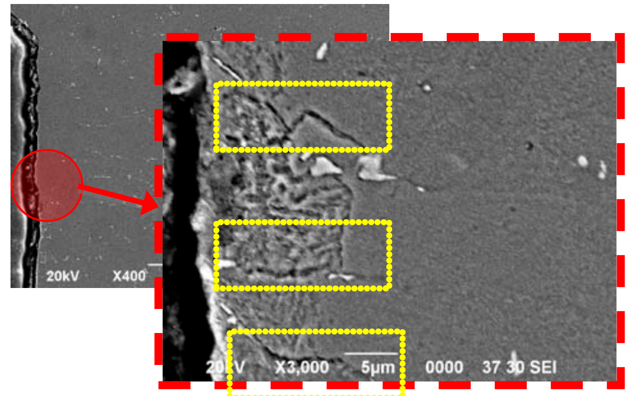

Fig. 11 : Microcracks detected with SEM on the HAZ area on SWET applied article at 200°C, 3000x

b) Microhardness Examination

Inconel 792 is nickel base precipitation-hardening cast superalloy that may be welded in the solution-treated condition because greater ductility of the base metal in the solid solution phase permits stress relaxation during welding. Inconel 792 has 1100-11500C gamma prime solvus temperature in where the solution heat treating at 11200C and the aging heat treating at 845oC is conducted (Donachie, M.J. & Donachie, S.J., 2002). The SWET technique may eliminate strain age cracking at base metal, weld metal, and heat-affected zone upon subsequent heat treatment to develop alloy mechanical properties.

Concerning the result of microhardness distribution shown in Fig. 12, it seems that the preheat temperature 200, 400, 600^{0}C have no significant influence to hardness distribution on HAZ and base metal, except hardness distribution on weld metal

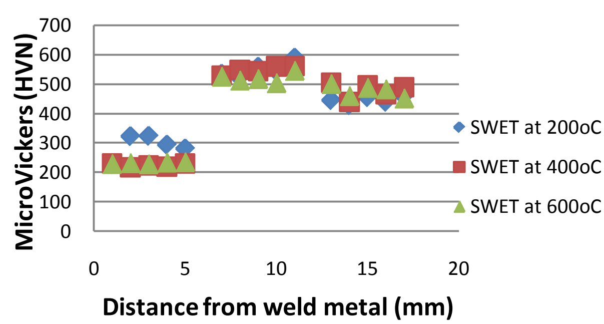

Fig. 12 : Hardness distribution on weld pool, HAZ, and base metal. Name of Machine: Zwick/ Roell Indentec

200^{0}C pre heating somewhat affect the increasing in hardness distribution in weld metal that may be caused by higher cooling rate resulting in smaller grain size in the weld pool. Fig.12 informed that an increase in the pre-weld heat treatment temperature increased the grain size but the hardness decreased, although the hardness of 718 Plus alloys was still greater than that of Inconel 718 (Vishwakarma, K.R., et al., 2005). However, the disadvantage of 200^{0}C preheating is inducing the availability of micro cracks.

c) Advantage of SWET

- Drive away moisture and contaminant from the weld area.
- The slower cooling rate provides an opportunity for hydrogen that may be present to diffuse out harmlessly, reducing the potential for cracking.
- Reducing temperature gradient during welding operation, minimize excessive residual stress, thus reducing chance of cracking.
- More controlled heating and cooling on the material, resulting better microstructure.
- Slow down the cooling rate in the weld metal and base metal, producing a more ductile metallurgical structure with greater resistance to cracking.
- Amperage needed to achieve welding temperature are reduced, welding cost can be minimized.

VI. Conclusions

- This analysis study is based on the evidence of experimental investigation. The following is concluding remarks from this study.
- Inconel 792 is an as-cast nickel-base superalloy and has a difficult-to-weld characteristic
- Welding difficulty is due to its precipitation hardening profile. Welding cause thermal gradient which will induce precipitate formation. Hardening will trap excess stress which leads to cracking.
- Cracking commonly occurs on the HAZ where temperature could increase or decrease rapidly and non-uniform.
- SWET is an application which can solve these difficulties, increasing Inconel-792 part capability to be repaired. Heating article prior to welding will reduce differential of temperature adjacent to the welding area.
- Heating the article prior to and during welding should be done in temperature ranging from 500 ºC and 1010 °C.
- Heating will reduce cooling rate, resulting increased ductility and better microstructure.
- Welding technique suitable for SWET application on Inconel 792 is the Gas Tungsten Arc Welding. Because its capability to weld wide range of alloys, low cost equipment, and great quality weldment.
- SWET application not only creating a crack-free weldment, but also reducing welding cost by lowering amperage needed to reach arc of welding.

VII. Acknowledgments

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