HOT TEARING OF A POLYCRYSTALLINE INDUSTRIAL TURBINE BLADE WITH TWO DIFFERENT NICKEL BASE SUPERALLOYS

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Abstract

The effect of chemical composition on hot tearing susceptibility of a polycrystalline industrial gas turbine blade during casting process has been investigated. Five master melts from two different nickel base superalloys by nearly similar chemical composition have been used for this purpose. The results show that in IN738-LC alloy, hot tear sensitivity has a direct relation with Zr content, but in Rene80 the amount of Zr, doesn't have any obvious effect on the hot tearing susceptibility of alloy. It could be related to lower HSC parameter in Rene80 alloy in comparison with that in IN738-LC. Besides the amount of Cr and Al which are the most segregating elements next to eutectic phase, in the IN738-LC are higher than that in Rene80 alloy.

Keywords: Turbine blade, investment casting, hot tear, Rene80, IN738LC

1. INTRODUCTION

Hot tearing is one of the most significant defects encountered in casting process which occurs in the last stage of solidification when the fraction of solid is close to one. The formation and propagation of the hot tearing have been found to be directly affected by the cooling history [1, 2], the chemical composition and mechanical properties of the alloy [3-8], as well as the geometry of the casting and ceramic shell characteristics [9].

The effects of cooling condition on the hot tearing of nickel base superalloys have been studied by Norouzi & Farhangi [2]. Increasing cooling rate has two opposite side effects. It increases thermal gradient, so enhances hot tearing tendency. In the other hand, the grain size and dendrite arm spacing decrease due to increasing cooling rate. Decreasing the dendrite arm spacing has two effects; increasing the strength of the material and dispersion of fine eutectic phase through the structure. Starting solidification ignite a competition between increasing the strength of the material and increasing the thermal stress. If the rate of increasing the material strength is superior to enhancement of thermal stress, this material will bear such a detrimental stress. In this case, there will not be a hot tear the case. Zhou & Vole [1, 10] found similar results in their studies. Their results show that the hot tearing tendency of the alloy is reduced by increasing GB fraction. The eutectic melt is finely dispersed and the strain at each individual GB is less as the GB fraction is increased. The better castability due to higher GB fraction is attributed to the stronger GB cohesion and more uniform distribution of strain [10]. Also they found that smaller dendrite arm spacing reduces the hot tearing tendency. The eutectic melt is more finely dispersed and increasingly discontinuous as the dendrite arm spacing is reduced [1].

The effects of chemical composition on hot tearing of nickel base superalloys have been studied by many researchers [3, 5, 7, 8]. Their results for IN738LC alloy show that grain boundary strengthening elements like Zirconium and Boron increase hot tearing tendency of alloy; but this theory haven't been generalized for other alloys. Zr and B promote grain boundary strengthening of superalloys, so their decrement, diminish stress rupture life of alloys. This study compares the effect of Zr level on hot tearing susceptibility of both IN738LC & Rene80 alloy for a similar part.

2. EXPERIMENTAL

In this study, 5 batches of a rotating industrial turbine blade have been casted from IN738LC and Rene80 nickel base superalloys. The wax patterns have been injected and then assembled in similar clusters. Ceramic slurry has been applied around the wax cluster using a robot dipping and stuccoing program. After de-waxing, similar wrapping technique has been used for controlling of heat transfer during casting and solidification for all ceramic molds. All ceramic molds were preheated before pouring. Two different master heats from each alloy have been used for these parts. The chemical compositions of the master heats are listed in **Table 1**. It could be seen that zirconium content is the main difference between master heats A and B. Also the amount of Zr in master heat D is about one fourth of that in master heat C.

Castability of master heats have been examined by considering hot tear crack observation during Non-Destructive Testing (NDT) including Grain size inspection, Radiography Testing (RT) and Fluorescent Penetrant Inspection (FPI). Also microstructural studies have been done using optical microscopy and scanning electron microscopy.

Table 1 Chemical composition of master heats (wt.%)

Batch Code	Alloy	Ni	C	Cr	Co	Mo	W	Nb	Ta	Al	Ti	B	Zr
A	**IN738LC**	Balance	0.11	15.9	8.3	1.7	2.5	0.8	1.7	3.5	3.5	100 ppm	500 ppm
B	**IN738LC**	Balance	0.105	15.8	8.32	1.76	2.69	0.77	1.59	3.49	3.5	100 ppm	50 ppm
A + B	**IN738LC**	50 % A + 50 % B											
C	**Rene 80**	Balance	0.165	13.75	9.95	3.85	4.15	0.04	0.03	2.95	4.96	120 ppm	400 ppm
D	**Rene 80**	Balance	0.16	13.92	9.20	3.96	3.98	0.02	0.042	2.96	4.84	130 ppm	110 ppm

3. RESULTS & DISCUSSION

Castability of master heats was examined by considering hot tear crack observation during NDT inspections (**Figure 1**). The normalized scrap rate of these five batches of parts is compared in **Figure 2**. Comparing master heats A, B and A+B, It could be seen that in equal amounts of alloying elements, the high zirconium alloy, is more prone to hot tearing. It could be related to effects of Zr on eutectic phase content and morphology.

It is well known that the surface tension of any solvent can be markedly reduced by the presence of relatively low levels of certain solute that are preferentially adsorbed at the surface or interface [11]. In the present case, one would expect a lowered surface tension of the residual liquid γ_{sl} when Zr content increases because of the enrichment of Zr in the liquid. When the surface tension of solid-liquid interface becomes lower than surface tension of solid- solid interface, complete wetting of grain boundary would be occurred that hinder solid- solid bridging. So a high concentrated alloying element region could be formed in this area that causes film shape eutectic phase formation. Tendency for hot tearing increases in this area because of:

1) Local lack of liquid feeding during solidification because of the higher γ/γ' eutectic phase volume fraction.
2) Weakening of alloy depleted zone next to eutectic phase.
3) Formation of brittle topologically closed packed (TCP) phases beside eutectic phase.

The film shape eutectic phases have been observed next to hot tearing cracks during metallographic investigations of master heat A and (A+B) (**Figures 3a** and **3c**). It could be seen that for these samples, crack propagation occurs along continuous film shape eutectic phase at grain boundaries. Besides, the SEM image (**Figure 4**) shows alloy depletion zone and oxides next to the crack which are main characteristics of hot tearing in nickel base superalloys. The analysis of oxides next to crack demonstrates that they are Al rich oxides;

however Cr and Ti are the main element in the oxides which are present in the crack. For master heat B, it is obvious that discrete eutectic phases distributed at grain boundaries (**Figure 3d**).

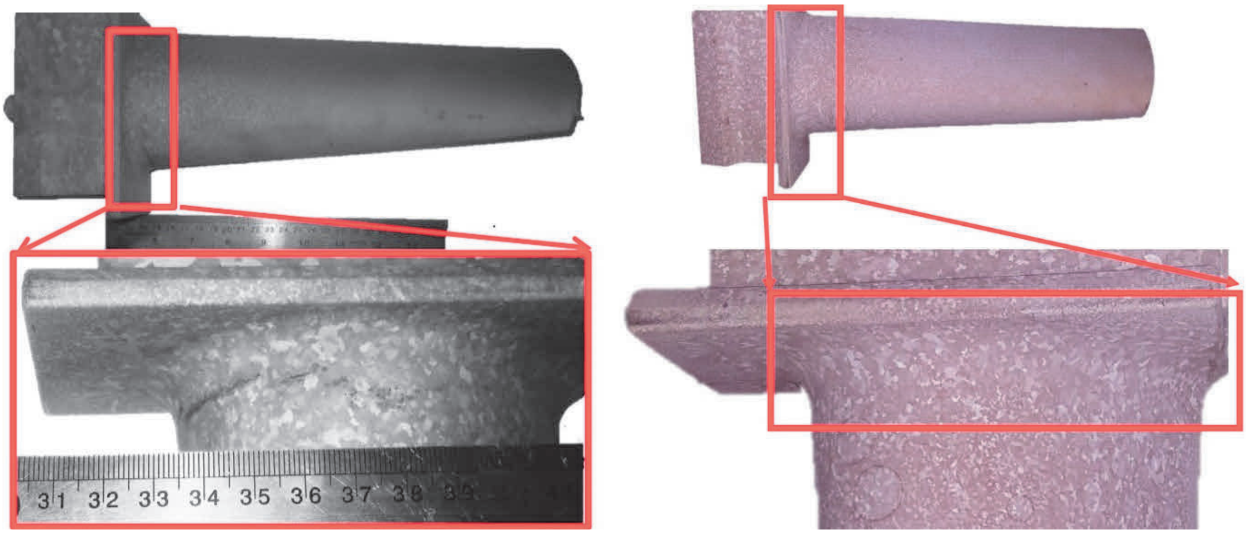


Figure 1 Location and general view of hot tear cracks in the part with master heat A (left). Lack of any crack in the part with master heat C (right)

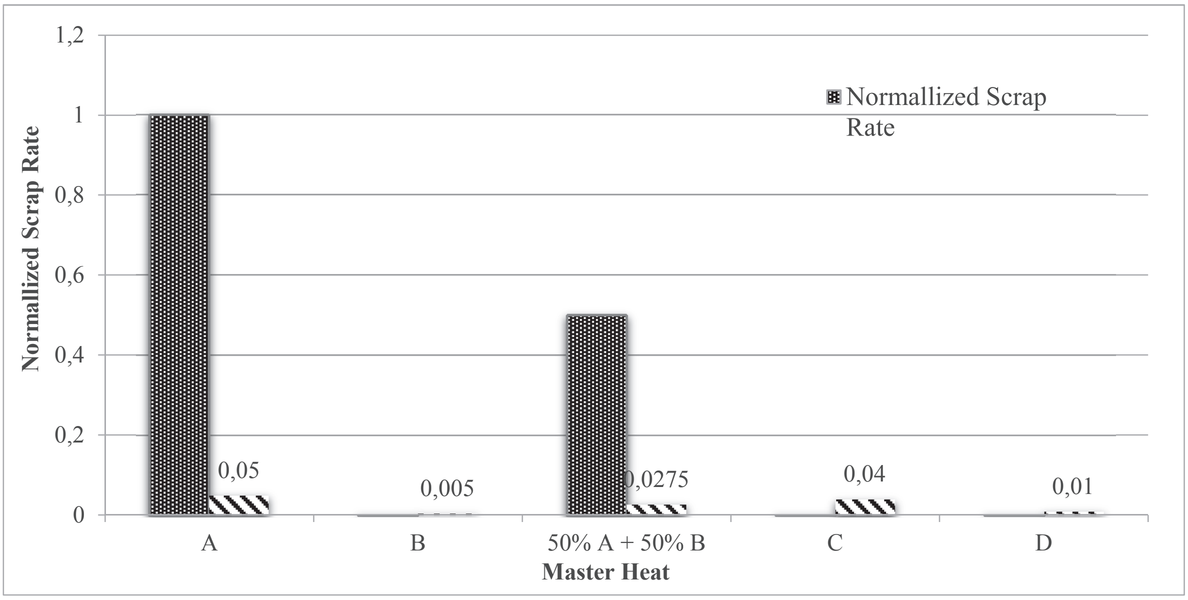


Figure 2 Normalized scrap rate of parts produced by these 5 batches. Observation of hot tear cracks was the criterion for rejection of parts. All parts produced by master heats B, C and D accepted in NDT inspections.

On the other hand, Rappaz et al. [12] showed that trans-granular coalescence occurs at a low solid fraction, while grain coalescence (inter-granular) takes place much deeper in the mushy zone at a higher solid fraction around 99%. They have derived the under cooling required for coalescence of two different grains assuming no inter-dendritic phases are present in the liquid film. This under cooling is a function of grain boundary energy (γ_{gb}) depending on misorientation between two grains, solid/liquid interfacial energy (γ_{sl}), entropy of fusion (ΔS_f) and thickness of the liquid film (δ):

$$\Delta T_b = \frac{\gamma_{gb} - 2\gamma_{sl}}{\Delta S_f} \frac{1}{\delta} \text{ [12]} \tag{1}$$

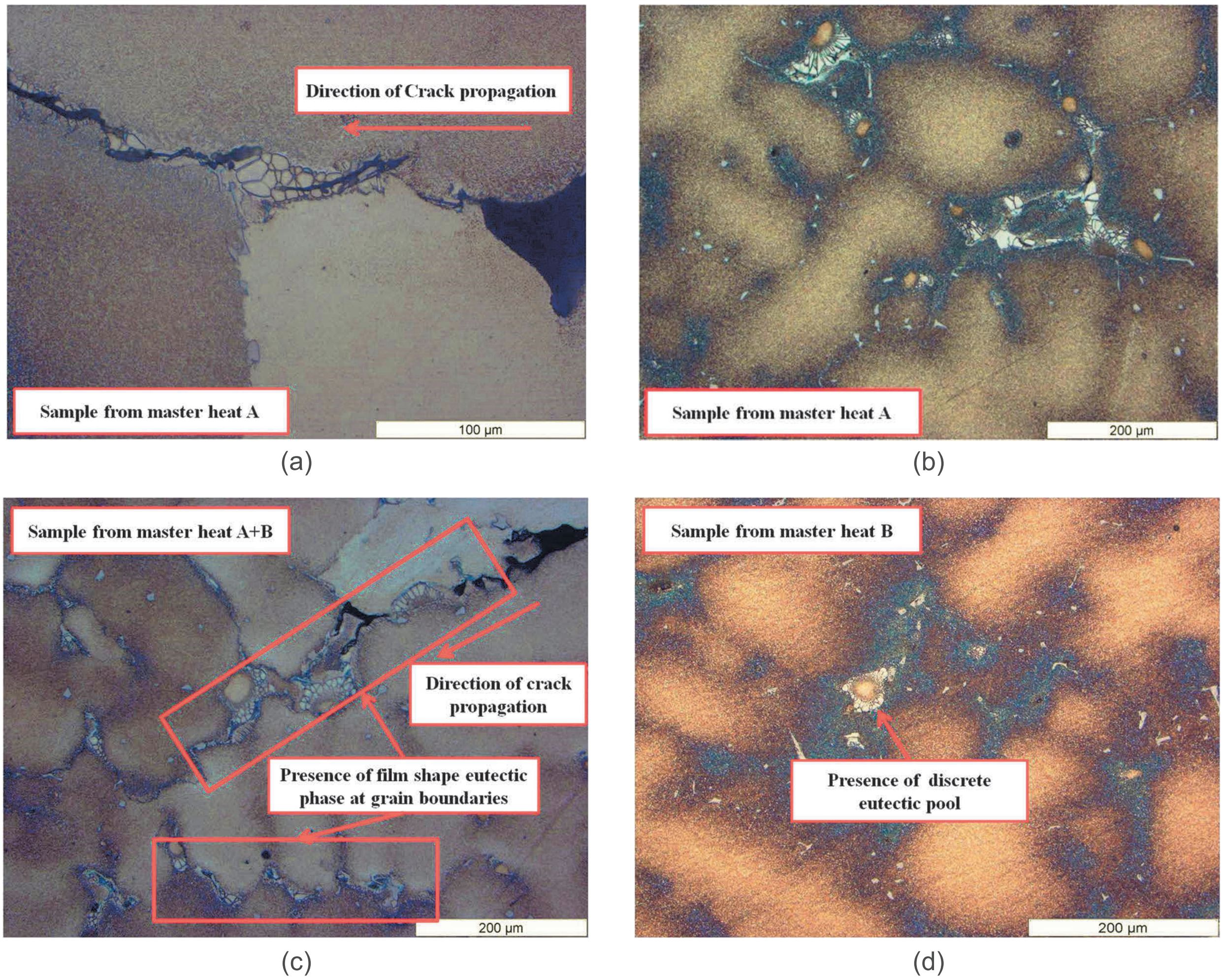
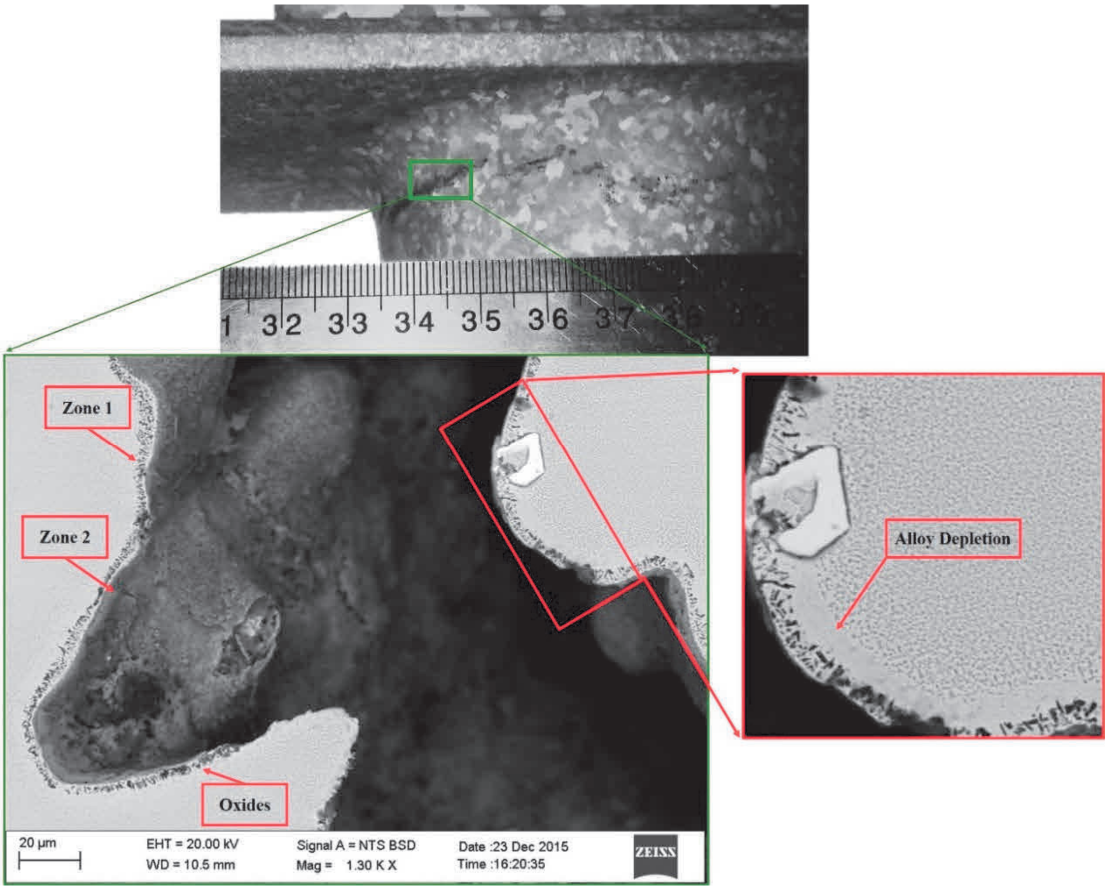


Figure 3 Optical micrographs comparing microstructure of 4 master heats a) Master heat A: Crack propagation along continuous film shape eutectic phase at grain boundaries b) Master heat A: Presence of a large amount of eutectic phases in the microstructure. c) Master heat A+B: Crack propagation along continuous film shape eutectic phase at grain boundaries d) Master heat B: Presence of discrete eutectic phases in the microstructure

It could be seen that reduction in γ_{sl} increases under cooling required for coalescence of two different grains. So it could be derived that in similar cooling condition, the time spent by the mushy zone in the vulnerable region in low γ_{sl} alloy is higher than high γ_{sl} alloy. Clyne and Davies [13] have recognized that hot tear is due to an opening of the mushy zone in a susceptible region where the dendrite arms can be pulled apart easily; so they developed a criterion for hot tearing sensitivity based on the time spent by the mushy zone in the critical zone, where continuous liquid film exist, but its permeability is too low to allow feeding. Their criterion can be expressed as:

$$HSC = \frac{t_V}{t_R} = \frac{t_{fs} = 0.99 - t_{fs} = 0.9}{t_{fs} = 0.9 - t_{fs} = 0.4} \text{ [13]} \tag{2}$$

where t_V and t_R correspond to the time spent by the mushy zone in the vulnerable region and the time where feeding by the movement of the liquid (and solid) can occur and t_{fs} corresponds to time spent for reach a certain solid fraction. Any variation in ΔT_b by changing in the γ_{sl}, prolongs t_V and consequently increases HSC. So it could be said that higher Zr content, decreases γ_{sl}, causes increment in ΔT_b and t_V and consequently, enhances hot tear cracking sensitivity.



Element	Zone 1	Zone 2
Al	37.1	5.8
Cr	6.7	48.3
Ti	0.2	11.5
Ni	30.5	1.1
Co	4.3	-
O	21.1	33.3

Figure 4 SEM image of cracks in part produced by master heat A; The presence of alloy depletion and oxides which are the main characteristics of hot tearing in nickel base superalloys (at. %)

On the other hand, for Rene80 alloy, Zr content doesn't have any obvious impact on hot tearing tendency. Hot tearing crack have been never observed during non-destructive testing of parts which produced by master melts C and D. It could be attributed to the following reason.

Firstly, as it has been said earlier, Cr, Al and Ti are the main segregating elements next to hot tear crack tip in IN738LC alloy. The amount of Cr and Al in Rene80 is lower than that in IN738LC, therefore it could be said that Rene80 is less prone to eutectic phases and hot tear crack in comparison with IN738LC.

Moreover, the behavior of Rene80 and IN738LC alloys during solidification was simulated using Scheil solidification model. With regard to the fact that the behavior of alloy in the last stages of solidification directly affects hot tearing phenomenon and based on the fact that Scheil model gives more information about the last stages of solidification in comparison with other solidification models including Lever rule or Back diffusion model, Scheil model were employed in this case.

In order to investigate HSC criterion for this part, it is assumed that the thermal conductivity of these alloys are equal. Besides the same gating system, wrapping system and casting parameters were applied for production of this part with both alloys. Therefore it is possible to use temperature instead of time in HSC criterion (**Table 2**). It is obvious that for IN738LC alloy, the HSC parameter is far higher than that for Rene80 alloy which means lower tendency to hot tearing in Rene80 alloy.

Totally, it could be concluded that high Zr content in IN738LC alloy leads to strong inclination to hot tearing in the part, but in Rene80 alloy, Zr is not as detrimental as in IN738LC alloy.

Table 2 HSC criterion based on temperature for alloys A (IN738LC) and C (Rene80) [14]

Batch Code	Alloy	t_{fs} = 0.99 (°C)	t_{fs} = 0.9 (°C)	t_{fs} = 0.4 (°C)	*HSC* parameters
A	**IN738LC**	950	1178	1303	1.82
C	**Rene 80**	976	1131	1291	0.94

4. CONCLUSION

The present work indicates that in IN738-LC alloy, hot tear sensitivity has a direct relation with Zr content, but in Rene80 the amount of Zr, doesn't have any significant effect on the hot tearing susceptibility of alloy. It could be related to the lower Cr and Al content in Rene80 alloy. The EDS analysis of crack region in IN738LC alloy indicates that Cr, Al and Ti are the main segregating elements in eutectic phases and therefore next to hot tear crack. Additionally, HSC parameter in Rene80 alloy is less than that in IN738LC alloy. However it should be noticed that with assumption of equal thermal conductivity in these two alloys and similar gating and wrapping systems and the same casting parameters, temperature were applied instead of time in the calculation of HSC parameter.

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