Susceptibility of Ni-Based Superalloys to Hot Tears with Minor Element Additions

PURDUE MATERIALS ENGINEERING

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Hot tearing susceptibility was investigated through minor element additions. After casting four molds each separately doped with B, P, Si, and Hf, the microstructural changes were observed to determine correlations to hot tearing. The P and Hf-doped molds exhibited the worst hot tearing properties due to an increased difference in the equilibrium and non-equilibrium solidus during solidification, segregation, and eutectic pool clustering. According to the microstructures, the B-doped mold should have developed a hot tear because it behaved similarly to the P and Hf-doped molds. When casting Ni-based superalloys, elements that contribute to these properties should be avoided to decrease the likelihood of hot tearing.

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Project Background

Arconic Power and Propulsion is a leader in investment casting superalloys for use in aero engines and industrial gas turbines. A casting defect called hot tearing occurs upon the last stages of the solidification process. Eutectic pools solidify last; thus, grain coalescence makes it difficult to feed the interdendritic regions. This coupled with solidification shrinkage induced tensile stresses can initiate a hot tear along grain boundaries. The need of this project is to understand compositional effects on the tendency to hot tear and the interactions at and away from the grain boundaries of Inconel 738 (IN738) with minor element additions. The goal is to understand compositional effects on microstructure and the tendency to hot tear in IN738. The interpretation of these results can then be carried over to other families of superalloys to alleviate hot tearing during investment casting.

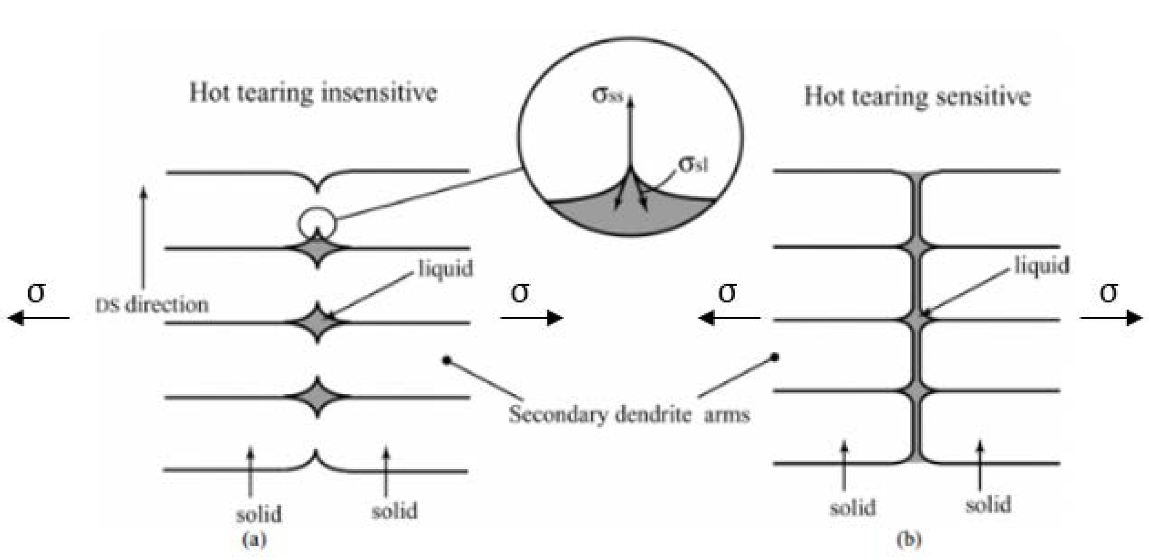

Figure 1:Schematic of (a) hot tearing insensitive and (b) hot tearing sensitive . Direction of the applied tensile stresses are indicated [1].

Experimental Procedure

Arconic investment cast four molds, each containing eight hot tear specimens, eight tensile specimens, and two chemistry slugs. Each mold had a minor element addition. Mold 1 contained 0.034 wt.% B. Mold 2 contained 0.009 wt.% P. Mold 3 contained 0.1 wt.% Si. Mold 4 contained 0.39 wt.% Hf. Boron was added because research suggests it segregates at the grain boundaries and weakens grain boundary coalescence. Phosphorus lowers final solidification temperature and has been linked to hot tearing in industry. Silicon was chosen because it is a tramp element and has been linked to increasing the area of the mushy zone. Hafnium segregates heavily but is the industry standard to prevent hot tears. [2]

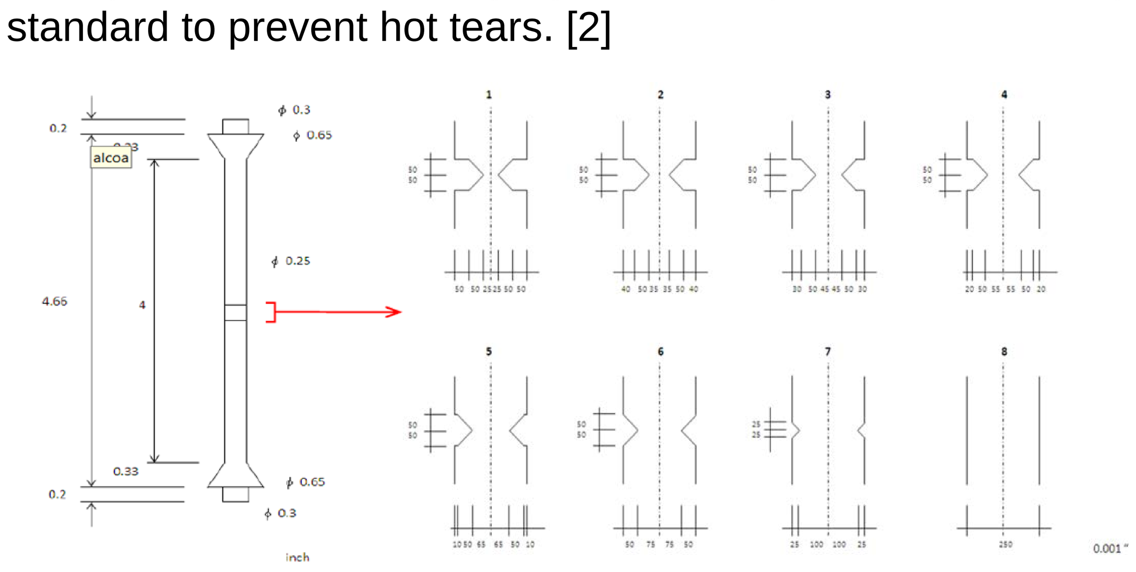

Figure 2: The geometry of the hot tear specimens investment cast by Arconic. Note the change in the notch for the hot tear specimens. The specimens with larger notches are expected to hot tear due to the geometric constraint

Figure 3: Image of Mold 1 before sectioning

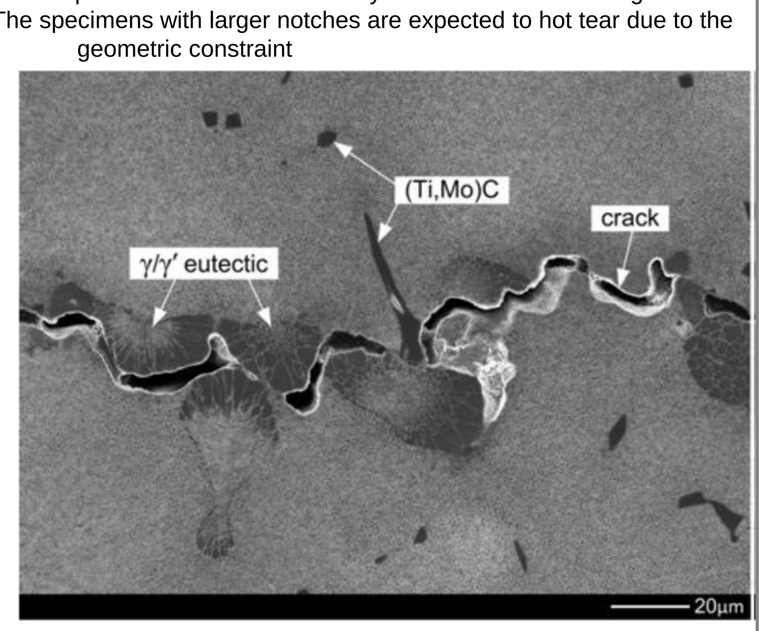

Figure 4: SEM image showing γ/γ' eutectic and MC carbide along a hot tear crack in IN100

High temperature tensile testing at 2000 °F was utilized to replicate intergranular fracture during solidification. Thermo-Calc software was utilized to investigate solidification behavior with element additions. The samples were sectioned, mounted, etched, and analyzed via optical and SEM microscopy.

Results & Discussion

Post Investment Casting Investigation

Table 1: A table containing observable hot tears after investment casting occurred.

Mold	Tensile Bar Specimen Hot Tear Count	Hot Tear Specimen Hot Tear Count
B-doped	0	0
P-doped	4	2
Si-doped	0	0
Hf-doped	3	0

Figure 5: Hot tear specimens (left) and tensile bar specimens (right) after being broken out from the mold and sectioned.

Table 1 contains a list of what molds had observable hot tears in the tensile bars and hot tear specimen bars. Of the 16 specimens cast, 6 had hot tears in the P-dope mold and 3 from the Hf-doped mold.

In the P-doped mold, hot tear specimens 1 and 2 exhibited a hot tear. This suggests that there is a correlation between constraint in the mold geometry and hot tearing susceptibility.

Equilibrium and Non-Equilibrium Solidification

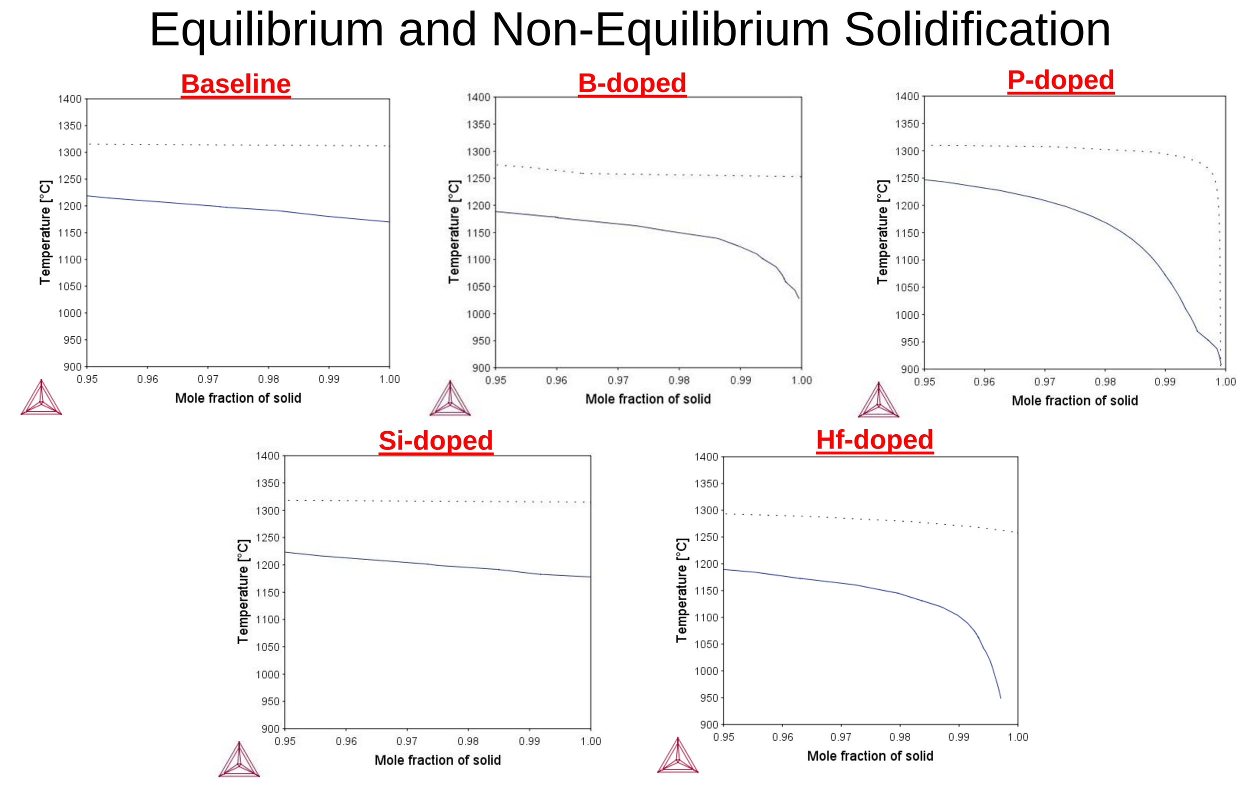

Figure 6: Scheil and Equilibrium solidification curves for the four altered chemistries.

Table 2: Scheil and Equilibrium solidification data for the four altered chemistries.

Solidification Simulation	Equilibrium Solidification Temperature (°C)	Scheil Solidification Temperature (°C)	ΔT_{E-S}	Composition of Last Liquid to Freeze (wt.%)	Percent Increase in Concentration
Baseline	1314	1177	137	-	-
B-doped	1253	1028	225	1.02	2900
P-doped	1117	908	209	0.73	8011
Si-doped	1312	1170	142	0.63	530
Hf-doped	1251	949	302	44.4	11,285

The Thermo-Calc analysis shows that all the doped chemistries, with the exception of Si, increase the equilibrium and non-equilibrium final temperature difference (ΔT_{E-S}) to above 200°C. Hafnium segregates the heaviest, followed by P and B. Silicon segregates the least and suggests it mixes better in Ni. It is hypothesized that the reason Hf and P experienced hot tears during solidification is due to the high levels of segregation these elements exhibit. Lower solidification temperatures coupled with segregation can promote eutectic pool formation and increase the amount of the last liquid to solidify. Increasing the amount of last liquid to freeze that is difficult to freeze in the interdendritic regions will increase hot tearing susceptibility.

Carbide Distributions & Volume Fractions

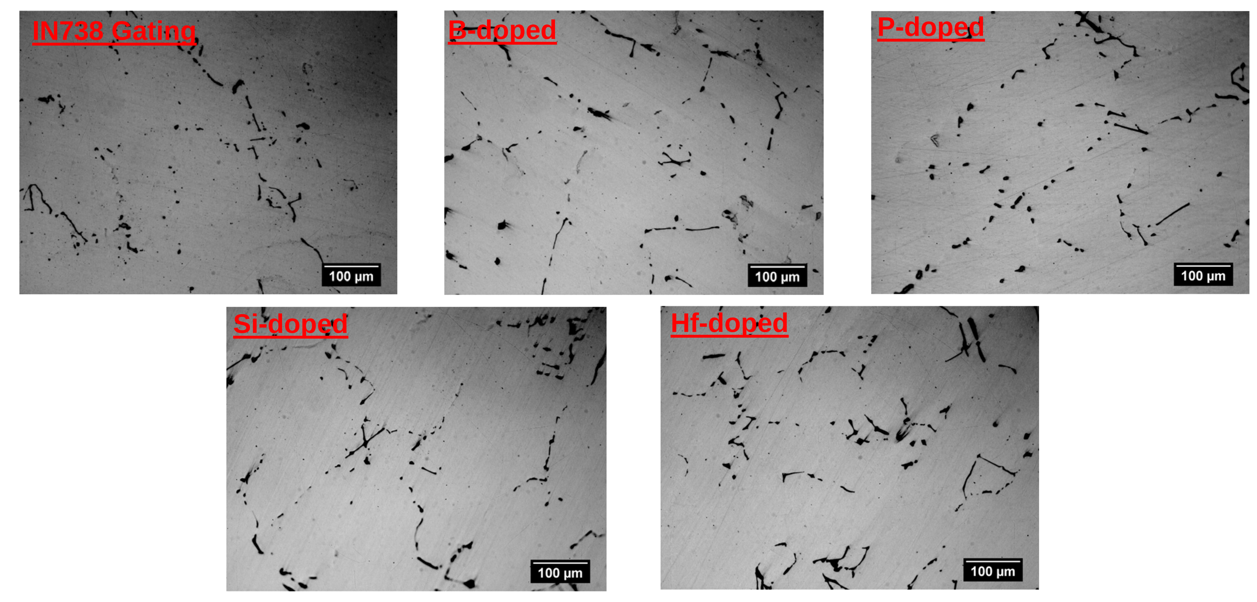

Figure 7: Unetched optical micrographs of undoped IN738 gating, B addition, P addition, Si addition, and Hf addition showing the carbides obtained from the chemistry slugs

Carbide morphology and volume percent were found to be similar across all samples. The volume percent of the IN738 gating, B-doped, P-doped, Si-doped, and Hf-doped were 1.35%, 1.91%, 2.44%, 2.31%, and 1.81% respectively. Due to similarities in carbide morphology and volume percent, carbides are not believed to be related with the observed hot tearing behavior.

Correlation of Tensile Fracture Surfaces with Eutectic Pool Morphology

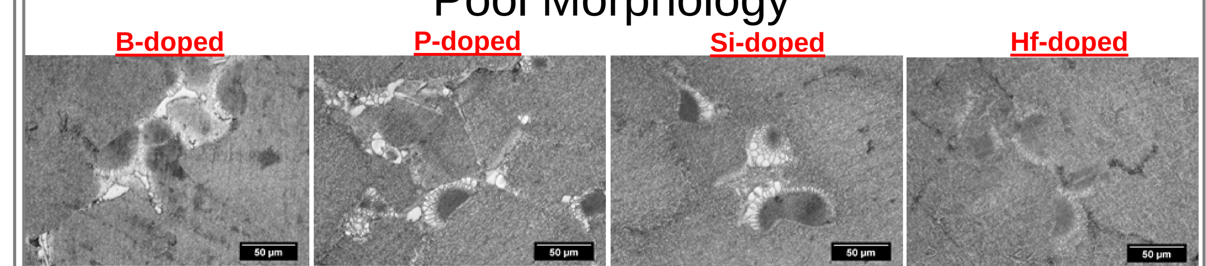

Figure 8: Optical micrographs of eutectic pools obtained from the chemistry slug specimens.

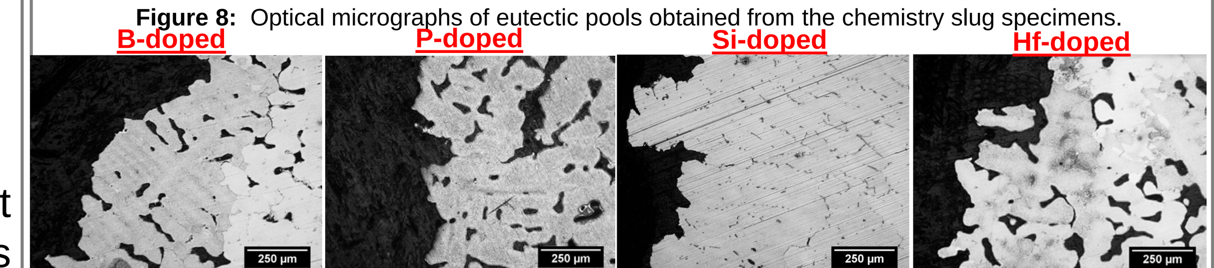

Figure 9: Optical micrographs of the high temperature tensile test fracture surfaces taken longitudinally.

Table 3: Data of eutectic pool volume fractions away from fracture, volume percent of voids near the fracture, and the average maximum eutectic pool clustering length of the tensile bar specimens. .

Mold	Eutectic Pool Volume Fraction Average and Standard Deviation	Average Max Eutectic Pool Clustering Length and Std. Dev (μm)	Volume Percent of Voids Near Fracture Surface and 95% C. I.
B-doped	0.14 ± 0.05	342.5 ± 86.7	8.3 ± 2.5
P-doped	0.14 ± 0.09	395.6 ± 17.3	16.1 ± 6.7
Si-doped	0.04 ± 0.02	89.8 ± 17.3	0.5 ± 1.6
Hf-doped	0.14 ± 0.06	242.5 ± 47.6	8.8 ± 2.1

Boron pools tended to be thick in both directions and cluster often. Phosphorus pools are longer and thin and experience the heaviest clustering. Silicon pools are large but isolated. Hafnium had pools were largest but were very spread out throughout the microstructure with the least amount of coarse gamma prime. Large and long eutectic pools creates a torturous feeding path. The voids in the high temperature tensile specimens, caused by tensile stresses during tensile testing, take on the shape of the eutectic pools and occur between dendrite arms. This is where eutectic pools form as solute is partitioned to the interdendritic regions during solidification. The Si-doped sample has the fewest voids as well as the lowest volume fraction of eutectic pools. Under solidification stresses these areas are the first to separate and provide paths for hot tears to form.

Observed Correlations

- Boron, P, and Hf-doped molds had a ΔT_{E-S} above 200°C creating microstructures with large eutectic pool volumes and heavy clustering. By lowering the composition of elements that lower solidification temperatures, promote segregation, and increase the eutectic pool clustering, hot tearing susceptibility can be decreased.
- The baseline and Si addition showed a ΔT_{E-S} below 200°C. The solidification behavior of the Si addition was similar to the baseline. The Si-doped molds exhibited microstructures with isolated eutectic pools and little clustering leading to low hot tearing susceptibility.
- Clustering of eutectic pools along grain boundaries could be pulled apart more easily during solidification to form a hot tear. Phosphorus and Hf-doped molds developed hot tears during casting and showed significant eutectic pool volume fraction and clustering.
- Molds with high eutectic pool clustering formed more voids during high temperature tensile testing showing the ability to pull apart eutectic pools. Phosphorous-doped molds had the most voids from the tensile test showing the weakest intergranular constituents which led to the most hot tears during casting.

Recommendations

Future work can include looking at solidification rates in the alloys. By decreasing solidification rates, the ΔT_{actual} would become less than the ΔT_{E-S} . From the results seen in the Si-doped mold, this would decrease the susceptibility to hot tear. Other future work can include using an alloy that has hot tearing problems to observe if additions can decrease hot tearing susceptibility. The B-doped mold's microstructure was similar to that of P and Hf-doped molds, yet exhibited no noticeable hot tears. More research into B should be made. X-ray Photoelectron Spectroscopy can provide quantitative chemistry distribution and segregation data.

References

[1] Zhang, J., & Singer, R.F. R.F. (2004). Effect of Zr and B on Castability of Ni-Based Superalloy IN792. *Metallurgical and Materials Transactions*,1337-342.

[2] Radavich, J.F. (1979). A decade of study of Hf modified alloys. *High Temperatures Seminar Report*, Purdue University, 152-153