AN EXAMINATION OF THE IMPACT OF GRAIN STRUCTURE ON TENSILE TEST RESULTS

ABSTRACT

Many of the common metal specifications include heat qualification testing requirements that must be met by casting and testing tensile bars. Controlling the grain structure of the cast tensile bars is a key component in obtaining consistent tensile results. Ideally, the grain structure in the gage section of a tensile bar will be a fine equiaxed structure. This structure will give consistent results that are representative of the capability of the metal. If the structure instead consists of large oriented grains, the tensile test results will be impacted by that orientation. In addition, if the grain orientation is not constant between tensile bars, the tensile test results may show significant variability. A study was undertaken to examine how different tensile bar styles will give different gage section grain structures. The resulting grain structures were then related back to the tensile properties of the test bars.

BACKGROUND

Impact of Grain Size and Structure on Mechanical Testing

In addition to meeting a given chemistry range, most metal specifications include a requirement that the material must meet certain mechanical properties when tested. Typically, the mechanical properties are verified by casting and testing tensile bars. Some common mechanical properties that are tested are tensile strength, yield strength, percent elongation, and stress rupture properties.

The size and structure of the grains in a polycrystalline metal strongly influence the mechanical properties of the material. This is because grain boundaries will act as a barrier to dislocation motion during plastic deformation.

Generally speaking, a fine grained material will be harder and stronger than the same material exhibiting a coarse grain structure. This is due to the fine grained material having a greater total grain boundary area to inhibit dislocation motion. This relationship between the yield strength and the grain size can be generalized by the Hall-Petch equation:

$$\sigma_y = \sigma_O + k_y d^{-1/2}$$

where d is the average grain diameter and σ_y and k_y are material constants[1].

In addition to grain size, the orientation of the grains may also influence the mechanical properties of the material. An extreme example is shown in Figure 1, where the mechanical testing results would be different depending on if the material was tested in the x or y-direction. The impact of grain orientation can be particularly important when there are coarse grains in the gage section of a test bar.

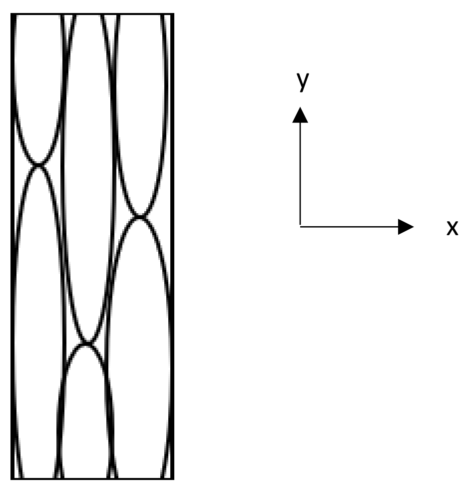


Figure 1: Schematic depiction of a material with grain orientation.

Lastly, a metallurgically sound casting is important for obtaining reliable, repeatable mechanical testing results. Figure 2 depicts a cast tensile bar with significant porosity in the gage section. The amount of porosity present in Figure 2 can often lead to failing or non-repeatable test results.

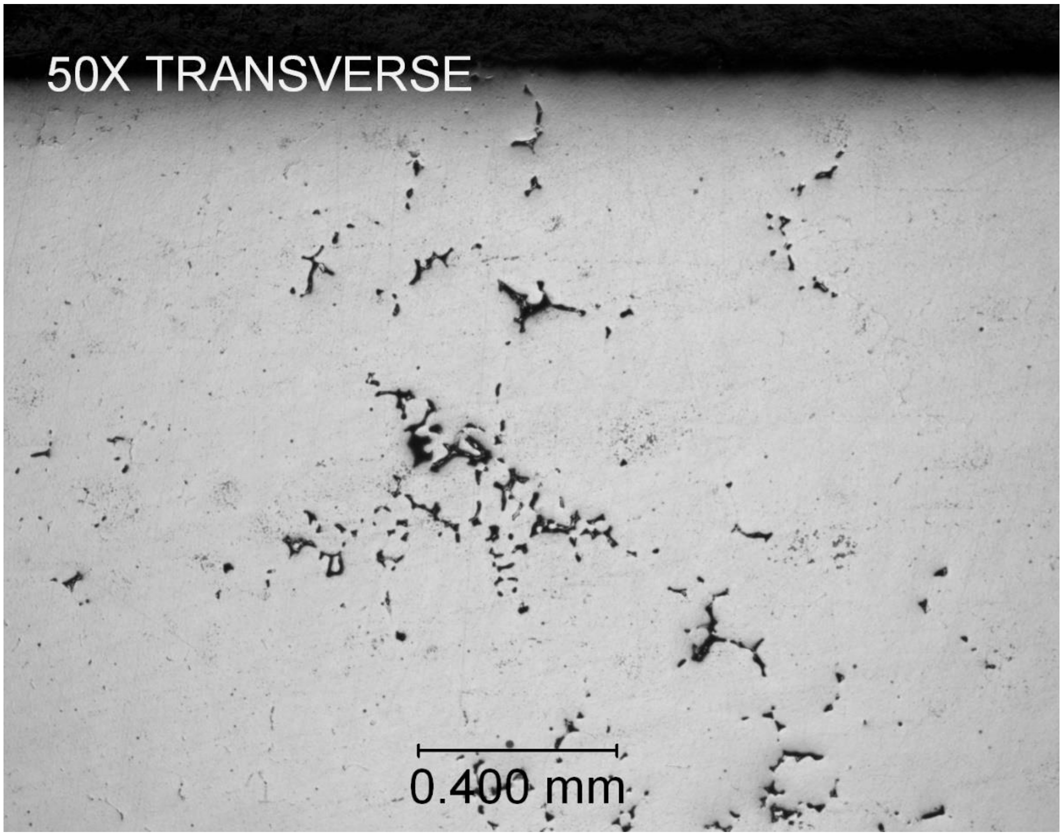


Figure 2: Porosity present in the transverse direction of a cast 347 steel test bar.

Impact of Casting Conditions on Grain Size and Structure

There are multiple casting conditions that will impact the final grain size of a cast part. These conditions include, the chemistry of the alloy, the pour temperature, the temperature of the mold, the shape of the part being cast and the associated gating.

The chemistry of a given alloy will play a role in grain structure of the solidified part. In particular, the difference between the solidus and liquidus temperatures (the freezing range) will be important in the formation of porosity in the casting. Alloys that exhibit a wide freezing range will be more difficult to cast fully sound than an alloy with a narrow freezing range. This is because a wide freezing range will allow more shrinkage to occur, which could result in increased porosity in the casting if the shrinkage isn’t adequately fed.

A large temperature gradient is a key factor in making a sound casting that has a small grain size because it promotes rapid solidification and minimizes the opportunity for grain growth. The pour temperature and the temperature of the mold are obvious factors that will influence the temperature gradient. A pour temperature should be chosen such that it utilizes the minimum amount of superheat required to cast successfully. A low amount of superheat will require less heat to be extracted from the metal and will promote grain nucleation and help minimize grain growth. Similarly, a low mold temperature will promote a larger temperature gradient and help minimize grain growth. The desire the minimize the pour temperature and mold temperature will need to be balanced by the requirements to fill the mold completely and make a sound casting.

The shape of the casting will also impact the cast grain size. Large sections will typically have larger grain sizes than small sections due to the more efficient heat extraction in the small sections which will help to minimize grain growth. In the case of cast tensile bars, the size and shape of the section of the casting that will become the gage section can influence the grain size.

The gating of the tensile bars may also play a role in the final grain size of the gage section. A gate connected to the gage may promote a sound casting with minimum porosity, however it may also serve as a heat source. This could reduce the temperature gradient in that area of the tensile bar and cause grain growth to occur.

This brief review of casting variables is not meant to be an exhaustive list and the book Castings[2] by John Campbell is recommended for a more in depth discussion of the metallurgy behind the casting process.

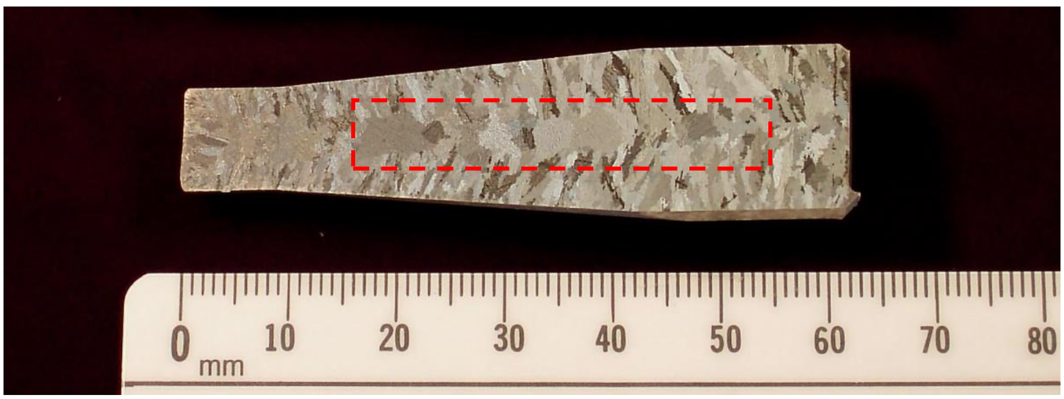
EXPERIMENTAL PROCEDURE

Two types of mechanical test bars were evaluated for this study. One type was a carrot-style test bar (Figure 3) and the other type was an hourglass style (Figure 4). Both bars were cast from a heat of IN 713 LC, the nominal chemistry of which is presented in Table I. Both types of mechanical test bars were sectioned, polished, and etched to allow the grain structure to be evaluated. The mechanical testing performed was room temperature tensile testing and stress rupture testing and were compared to the requirements of AMS 5377.

Table I: Nominal composition of IN 713 LC

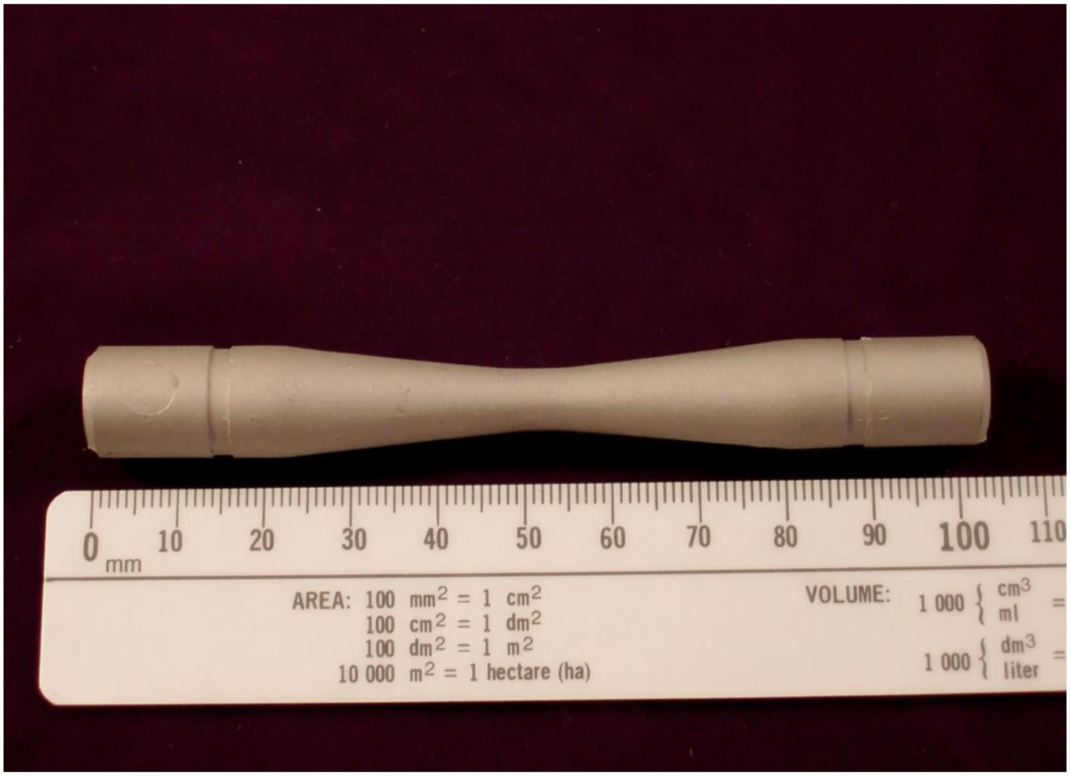
C	Cr	Ni	Mo	Nb/Cb	Ti	Al	B	Zr
0.06%	12%	Bal.	4.3%	2%	0.7%	5.8%	0.007%	0.06%

(a)

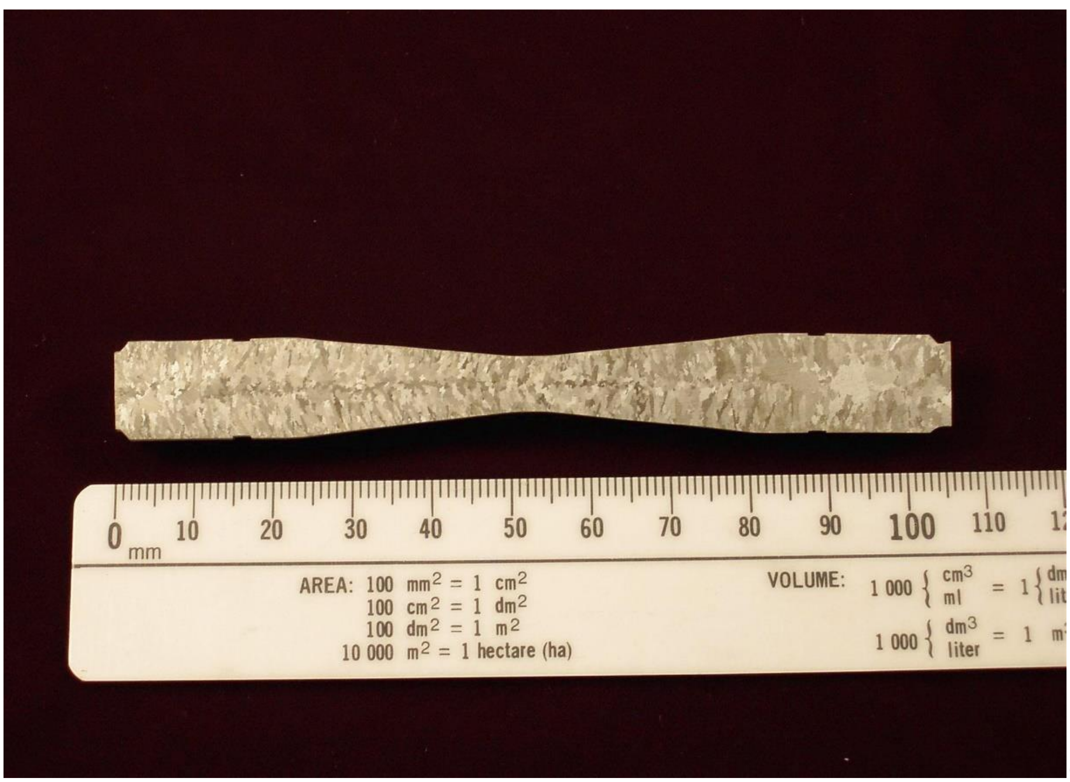


(b)

Figure 3: (a) Carrot-style test bars of 713 LC. Note the presence of large equiaxed grains in the center of the tensile bars. (b) Schematic overlay of the part of the test bar that will become the gage section once the test bar is machined. Note the gage section will consist of a predominately coarse grain structure.



(a)



(b)

Figure 4. Hourglass shaped test bar of 713 LC. Note the fine-grained structure through the gage section of the test bar in photo (b).

RESULTS AND DISCUSSION

The grain structure of the carrot shaped bars can be observed in Figure 3. There is no apparent porosity in the bars, which indicates that the carrot shape is capable of producing a sound casting. The grains in the center of the bar, however, are large relative to the overall size of the bar. When the test bars are machined to produce tensile bars that will meet ASTM E8, the gage section will consist predominately of the large grains. This is illustrated schematically in Figure 3b where the dashed red lines indicated the gage section of a tensile bar that would be machined from the carrot bar.

Figure 4b presents the grain structure of the hourglass shaped bars. The grain structure in the gage area is fine compared to the structure in the carrot shaped bar. Minimal machining will be required to be done to the hourglass shaped bars so the test area will consist of a fine grained structure.

The room temperature tensile results of the test bars are reported in Table II. All bars met the minimum yield, tensile and elongation requirements. Comparing the two test bar shapes shows that the hourglass type bar exhibited a lower yield strength, higher ultimate strength, and higher elongation than the carrot shaped test bars.

Table II: Room temperature tensile results for Carrot and Hourglass shaped test bars

Test Bar Shape	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**	**4D Elongation (%)**
Carrot	820	995	10
Carrot	798	959	11.2
Hourglass	783	1014	13.6
Hourglass	732	974	14.1
AMS 5377 REQUIREMENTS	**690 MPa min.**	**760 MPa min.**	**5% min.**

The results of the stress rupture testing are reported in Table III. The hourglass shaped bars passed all requirements under all test conditions. In addition, there was good agreement between the test bars. The carrot bars however, experienced multiple failures to pass requirements. Of the five samples tested, only 2 samples passed the minimum elongation requirement and no samples passed the minimum rupture life requirement.

The differences between the carrot and hourglass shaped test bars are likely due to the differences in the grain structures seen in Figures 3 and 4b. The fine equiaxed grain structure of the hourglass shaped bars should give the most consistent and reliable mechanical test results that will be representative of the alloy. This is because the equiaxed structure will not show a grain orientation dependence and smaller grain sizes typically result in increases in mechanical properties. The mechanical properties of the carrot shaped test bars will be highly dependent on the limited number of coarse grains found in the gage section and on the orientation of the coarse grains. The dependence on the grain orientation can lead to increased variability in mechanical testing results.

Table III: Stress rupture results for Carrot and Hourglass shaped test bars. Failing results are in red.

	Test Conditions	
	980°C/150 MPa	
Test Bar Style	**Rupture Life (h)**	**5D Elongation (%)**
Carrot	**22.3**	**2.5**
Carrot	**23.8**	**3**
Carrot	**28.3**	5
Carrot	**26.6**	5
Carrot	**28.4**	**2.5**
Hourglass	53.1	8.5
Hourglass	58.4	9.2
AMS 5377 REQUIREMENTS	**30 h min.**	**4% min.**

SUMMARY

Two different types of test bars, carrot shaped and hourglass shaped, were cast from the same heat of IN 713 LC. The grain structures in the gage sections of the bars were significantly different with the grain structure in the hourglass shaped bars being finer than the carrot shaped bars. The mechanical testing results from the two types of bars were also different, with the hourglass shaped bars passing all stress rupture requirements and the carrot shaped bars failing either the rupture life or elongation requirement. The most likely cause for the differences between the test bar types was the difference in the grain structures.

While this paper is not meant to give an exhaustive list of casting conditions and how they impact mechanical test results, the results that were discussed illustrate Cannon-Muskegon's belief that a fine, equiaxed grain structure will give the most consistent mechanical results that will be representative of the alloys capabilities.

RECOMMENDATIONS

It is recommended that casting facilities perform a grain structure characterization on their mechanical test bars as this will help with understanding mechanical test results. This is important even for facilities that are able to consistently pass mechanical test requirements. Having an understanding of the grain structure will be useful in diagnosing problems if unexpected failures begin to occur. In addition, facilities that have variable mechanical results would also benefit from understanding the grain structure of their tensile bars. If the test bars show porosity or coarse grains in the gage section, the variability of the test results may be due to the grain structure.

REFERENCES

1. Dieter, George JR. M*echanical Metallurgy*. 1961
2. Campbell, John. *Castings.* 1991