

ANALYSIS OF FATIGUE STRENGTH OF AUSTEMPERED DUCTILE IRON WITH DIFFERENT HEAT TREATMENT

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Abstract: *Austempered ductile cast irons (ADI) have received great attention in last years because their combined tensile properties with good ductility and fracture toughness and low production cost. However, fatigue properties of these materials are less known. The aim of the present study is to compare the fatigue strength of a ductile cast iron-Cu, Ni, Mo alloy which have received three different austempering heat treatment to produce ADIs with different tensile strength level, corresponding to the ASTM A897 grades III, IV and V requirements. Fatigue tests were performed under load control and with stress ratio equal to -1 to obtain the S-N curve of the materials with and without austempering heat treatment. In addition, tests were carried out to determine tensile properties of the alloy. Also microstructural characterization was performed using a scanning electron microscope (SEM). The first group of samples was austenitized at 910°C for 60 min and austempered at 320°C for 90 min; the second and third groups were austenitized at 930°C for 120 min, and then austempered at 300°C for 40 min and at 280°C for 40 min respectively; the fourth group were the as cast alloy. Tests were performed using different levels of amplitude, determined by the material ultimate tensile strength, in uniaxial teste using a Instron machine, model 8801. From the S-N curves, it was possible to obtain the values of fatigue limits of the materials. Based on the results obtained after austempering heat treatment, it was possible to observe changes in the fatigue strength of the alloy through the behavior of the S-N curves. This behavior could be correlated to the microstructural changes resulting from the austempering heat treatments performed.*

Keywords: *Mechanical properties, fatigue test, Fatigue limits, ADI.*

1. INTRODUCTION

The search for lighter, more durable and less expensive materials has always been one of the great demands in the world of engineering and in particular in automotive construction. For this reason, there is a continuous necessity to always bring new materials to the market and re-evaluate those already in service.

In the 1970s, through extensive studies and development of new technologies, the foundry industries improved the use of better continuous systems for the austempering heat treatment. When applied to commercial ductile iron alloys, this advance resulted in the large-scale production of a new type of material, the austempered ductile iron (ADI).

Several studies since then (Francklin, 2009; Lefevre and Harynen, 2013; Nofal, 2013) have shown that ADI even at high stresses has presented excellent mechanical properties, such as good strength and good ductility, thus providing an advantage in resistance to wear, fracture and fatigue compared to other materials. Some works (Cast Metals Development, 1992; Keough and Hayrynen, 2000) shows that in addition to its high strength ADI still has a 10% lower density than steel, thus providing a better ratio of weight to material and the strength.

In the same way, as other mechanical properties, the fatigue properties of ADI are strongly influenced by the microstructure. The microstructure on the other hand depends on the heat treatment, which influences the quantity, size

and distribution of the phases present in the alloy. However Dias (2006) in his work explains that the microstructure is also closely related to solidification, which defines the of graphite’s morphology (quantity, size and distribution), and defects (porosities, inclusions, segregations, second phase particles or eutectics).

According to several papers (Nofal, 2014; Takahashi, 2014; Israel, 2005), the heat treatment cycle responsible for the improvements of the mechanical properties of ADI basically consists of the austenitizing and austempering treatments in ductile iron parts. As can be seen in Fig. 1, the sequence of steps of this treatment consists in first heating the part to the austenitization temperature and after the complete austenitization of the material, cooling it abruptly to the austempering temperature, the material then remains at that temperature for a certain period and is finally cooled to room temperature.

In cast irons, this heat treatment cycle produces a structure formed by acicular ferrite and high carbon stabilized austenite. This structure has long been confused with bainite, a combination of acicular ferrite and iron carbides resulting from the austempering treatment in steels, some authors still call it pro-bainite, but the denomination that had greater acceptance was "ausferrite".

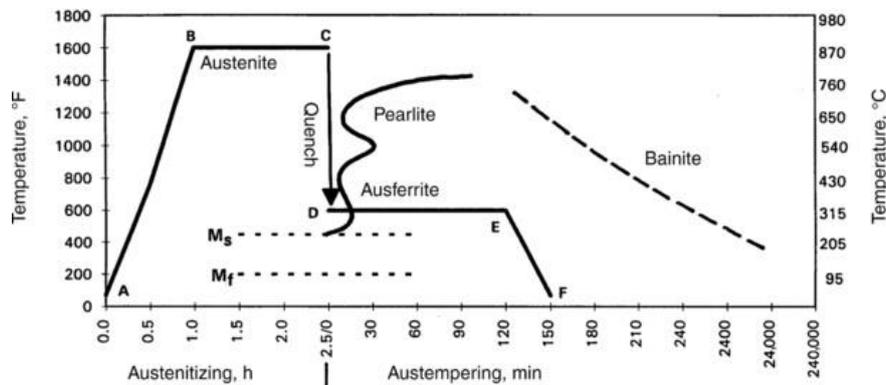


Figure 1. A Schematic of the austempering process (Hayrynen, 2002).

Austenitization in the ADI directly influences the chemical composition of the material after solidification. According to some works (Trudel and Gagné, 1997; Israel, 2005; Machado, 2007), the austenitization temperature controls the retained austenite content, which affects the mechanical properties of the austempered alloy. Therefore, there will be a decrease in the properties of the material as the austenitization temperature increases. This behavior is associated to the growth of grain size that would occur in the material as the austenitization temperature increases.

The austempering temperature ranges from 230 to 400°C depending on the mechanical properties to be obtained. Israel (2005), explains that for austempering temperatures above 350°C produce parts with ausferrite coarse matrix having moderate strength and hardness, but high ductility and toughness. When parts with high strength and hardness are necessary, sacrificing impact resistance, is recommended the use of lower temperatures, around 203 to 350°C.

This process of austempering in the ductile iron does not contain a single stage as in steels, but two. Baumer and Guedes (1989) describe that in the first stage, acicular ferrite nucleates at the graphite/austenite interface or in the grain outline of the austenite, and grows towards the interior of the austenite. In this process of nucleation and growth of the bainitic ferrite occurs the segregation of carbon to the primary austenite, due to the low solubility of the carbon in the ferrite. The solubilized carbon in austenite inhibits the nucleation and growth of ferrite platelets, promoting stability of the high carbon austenite. This reaction is represented by Eq. (1).



This equation shows the acicular ferrite (α) and austenite stabilized due to the high carbon content (γ_{HC}) resulting from the transformation of austenite saturated carbon (γ_c). The time at which the quantities of acicular ferrite and high carbon austenite remain constant represents the process window. Several studies (and Barry, 1989, Tanaka and Kage, 1992; Rundman et al., 1988) show that during the second stage, the precipitation of iron carbides begins to occur from the high carbon austenite, which weakens the material, and consequently is undesirable. This reaction is shown in Eq. (2).



Elliot (1988) comments that aiming to facilitate the production of the ADI, it is usual in the industries to separates the maximum these two stages, by adding silicon, since this element delays the formation of iron carbides, allowing the obtaining the ausferritic structure.

2. EXPERIMENTAL PROCEDURES

2.1. Material

In this work, fatigue smooth specimens of circular cross section have being machined from of a nodular Cu-Ni-Mg-cast iron bar produced by continuous casting. Figure 2 shows the geometry and the dimensions of the fatigue specimens. The nominal chemical composition of this alloy is presented in Tab 1.

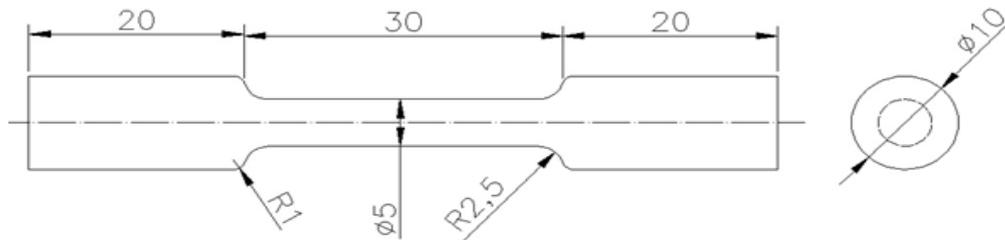


Figure 2. Fatigue samples dimensions.

Table 1. Chemical composition of alloy.

Chemical composition (wt %)									
C	Si	Mn	P	Mg	S	Cr	Cu	Mo	Ni
3.20	2.80	0.10	0.000	0.035	0.000	0.06	0.2	0.2	0.2
-	-	-	-	-	-		-	-	-
3.40	3.10	0.20	0.050	0.060	0.002		0.70	0.5	0.6

2.2. Heat treatment

The samples were divided into four groups and each group was subjected to different cycles of heat treatments. In the first group, no heat treatment was performed, thus serving as a comparison material for the results obtained through the thermal treatments performed in the other groups. In the second group the heat treatment cycle consisted of austenitization at 910°C for 60 minutes and austempering at 320°C for 90 minutes. In the third group the heat treatment cycle consisted of austenitization at 930°C for 120 minutes and austempering at 300°C for 40 minutes. In the fourth group the heat treatment cycle consisted of an austenitization at 930°C for 120 minutes and austempering at 280°C for 40 minutes.

2.3. Mechanical tests

Tensile and fatigue tests were performed at room temperature on each material group using an INSTRON 8801, servo-hydraulic machine with a capacity of 100kN. Tensile tests were performed at a strain rate of 0.2mm/min.

The tensile-compression fatigue tests were performed under load control until complete material rupture, according to the following characteristics: a constant stress amplitude, a fatigue ratio (R) of -1, a frequency of 10 Hz, and a runout of 2×10^6 cycles.

In order to obtain the S-N curves (stress amplitude versus the number of the cycles to failure), 12 samples of each group were tested at four different stress amplitudes levels. These S-N curves were obtained using linear regression of experimental data, according to Basquin, showed in equation Eq. (3), where b is the slope and log A is the intercept (Dowling, 1998):

$$S = AN^b \quad (3)$$

2.4. Microstructural analysis

Metallographic samples were taken from each of the heat treatments performed, including the as-cast alloy. These samples were prepared according to the standard procedures for analysis carried out in the scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

The mechanical properties of the tensile test are presented in Tab. 2 grouped according to austempering temperature. It may be noted that all three treatments produced performed ADI alloys with higher ultimate strength and yield strength of the as-cast alloy, however, it is observed a considerable decrease in elongation of the material for austempered materials.

Table 2. Mechanical properties of alloy

Austempering Temperature (°C)	Ultimate strength (MPa)	Yield strength (MPa)	Elongation (%)
As-cast	864 ± 114	673 ± 146	7.24 ± 5
320	1432 ± 59	1235 ± 113	3.53 ± 3
300	1602 ± 315	1405 ± 191	4.46 ± 3
280	1486 ± 51	1340 ± 17	2.09 ± 1

The S-N curves for the as-cast alloy and for each austempering temperature used are shown in Fig. 3 in a log-log plot. The data indicated in the curves with a black arrow represent the tests where no rupture has occurred (runout).

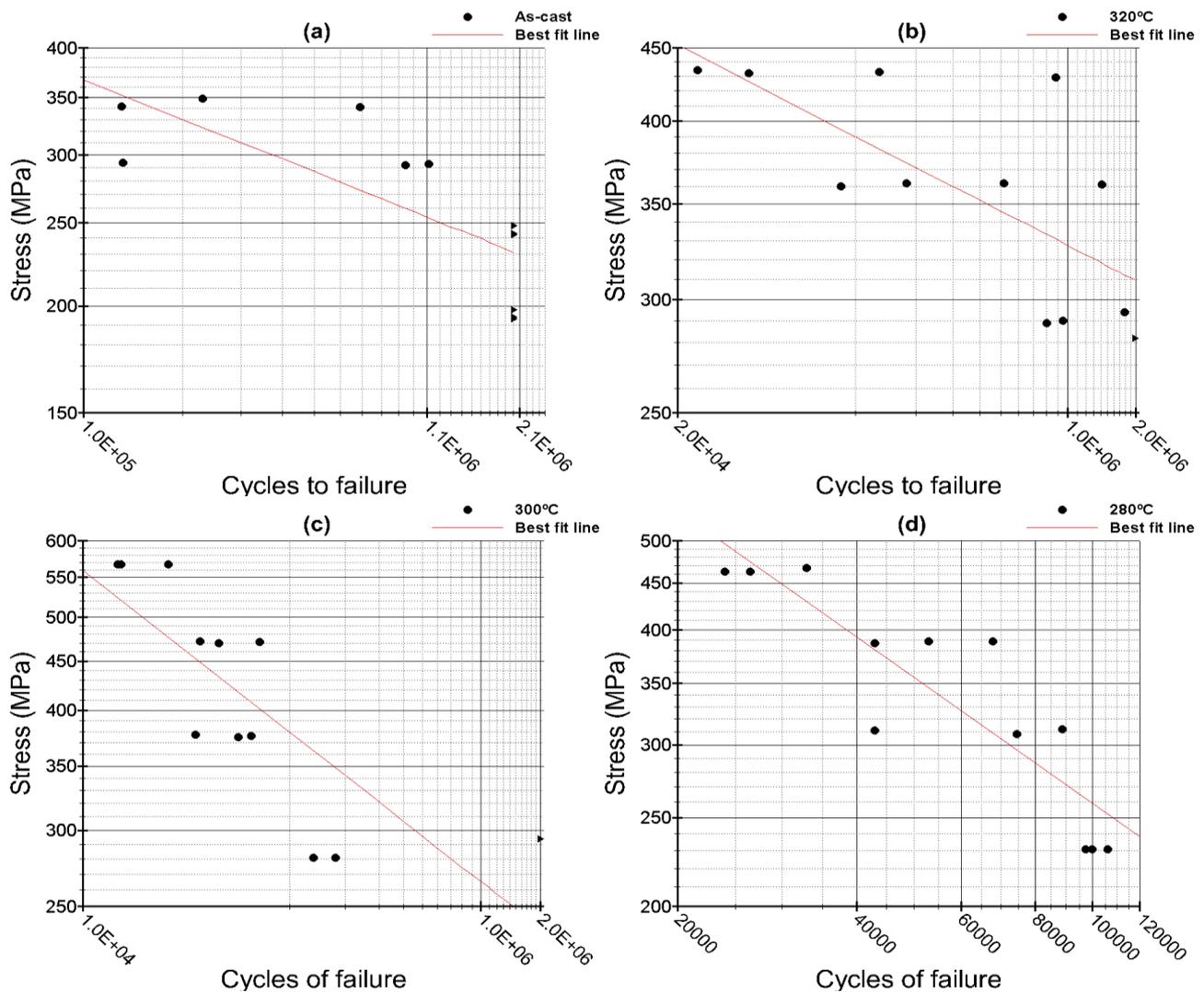


Figure 3. S-N curves of ductile iron in the (a) as-cast and austempering at (b) 320°C, (c) 300°C, (d) 280°C.

Analyzing the results, it is possible to observe a great dispersion in data for the same stress level, this coincides with what Castro (2007) found in his works on the study of the behavior to the fatigue of the metals, according to the author this characteristic is due to the sensitivity of the fatigue test to a variety of parameters and materials shows the statistical nature of fatigue and makes it very difficult to be controlled in a precise form.

Table 3 shows the coefficients found by the linear regression of the Basquim equation Eq. (3), used to construct the S-N curves of the alloy for each of the austempering temperatures seen in Fig. 4.

Tabela 3. Basquim constants for each austempering temperature.

Austempering Temperature (°C)	Basquim constants	
	A (MPa)	b
As-cast	2162	-0.153
320	1021	-0.082
300	2482	-0.161
280	49454	-0.456

A comparison of the S-N curves of each material can be visualized in Fig. 4. It is observed, through the S-N curves presented, that each austempering temperature used in the heat treatments gave different results when compared to the as-cast material.

The alloy austempering at 280°C, show for low-cycle fatigue, the best behavior in relation to the other curves, more precisely for stress above 480MPa in comparison to the alloy austempering at 300°C and 440MPa when compared to the as-cast alloy. On the other hand, the austempering alloy at 320°C provided the best high-cycle fatigue behavior at stress bellow 440MPa in relation to alloy austempering at 300°C and 410MPa relative to the alloy in the as-cast samples. Finally austempering alloy at 300°C presented a proportional increase, in relation to the as-cast alloy, for all stress levels.

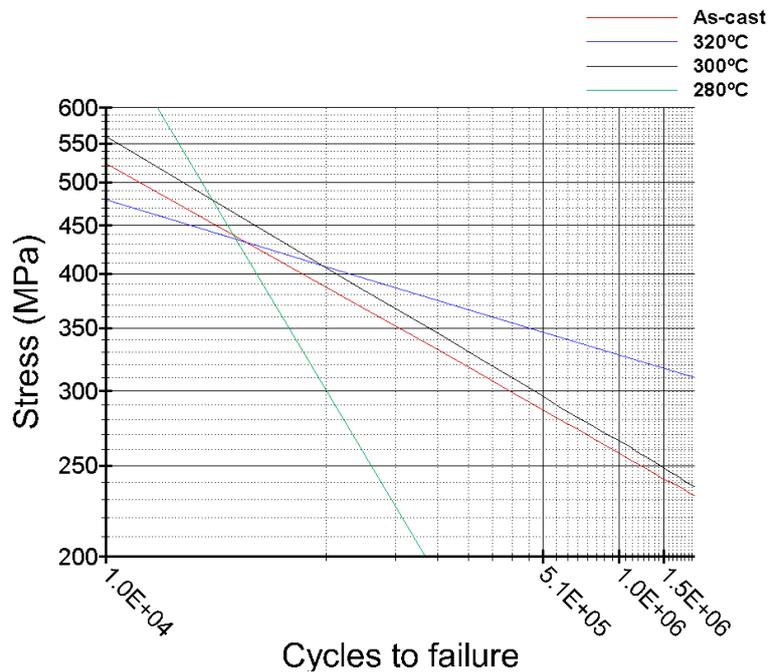


Figure 4. Comparison between the S-N curves of alloy.

As can be observed in Tab. 4, although, after the heat treatment, the alloy has shown a considerable increase in some of their mechanical properties, the behavior presented by the S-N curves of the alloy with and without the heat treatment shows a lack of correlation between the ultimate strength of the material with its fatigue strength for 2×10^6 cycles.

The behavior of the S-N curves presented in Fig. 4, correspond to the results found by (Alves et al, 2016) about the amount of austenite retained in these materials after the austempering treatments performed in each group of samples. According to the author the first group austempered at 320°C presented the highest amount of austenite retained with 27.30% of austenite, followed by the second group austempering at 300°C with 15.60% of austenite and finally the samples austempering at 280°C with 19.40% of austenite.

This behavior can be observed in several studies (Lin et al, 1996; Bahmani et al, 1997; Ovali et al, 2012), this is due to the composition of the alloy microstructure, and that is, the amount of retained austenite is a factor more relevant than the ultimate strength when analyzing the fatigue strength of the material.

Table 4. Relationship between the ultimate strength and the fatigue strength for 2×10^6 cycles.

Austempering Temperature (°C)	S (2×10^6) /UTS
As-cast	0.26
320	0.21
300	0.04
280	0.15

Figure 5 shows the micrograph of the alloy studied, for the as-cast state and for all the austempering temperature of the sample, in order to provide a comparison of the micrograph obtained in the treatments. In Fig. 5a one can see the as-cast material, with graphite nodules distributed in a matrix containing ferrite and perlite, it is also possible to visualize the effect usually known as bull's eyes, where the graphite is concentrated around the nodules of graphite.

Figure 5b-d shows the effects of austempering heat treatments on samples of the ductile iron alloy used. The first visible change in this heat treatment is in the matrix, which now is known as asferrite, composed of acicular ferrite, represented by the black needles and an austenite matrix, represented by the bright background. It is also possible to note that after the austempering heat treatments, the graphite acicular becomes thinner and closer as the temperature of the austempering decreases, theoretically making the matrix more resistant.

These results are in agreement with several studies (ASM Handbook, 1987; Zimba et al., 2003, Fernandino and Boeri, 2016) and can be observed through the images of the austempering alloy at 320°C where the acicular ferrite is coarse and dispersed, while at 280°C the ferrite needles are thin and close, containing a smaller percentage of austenite retained in the samples. The effect of the retained austenite volumetric fraction can be further investigated in more details.

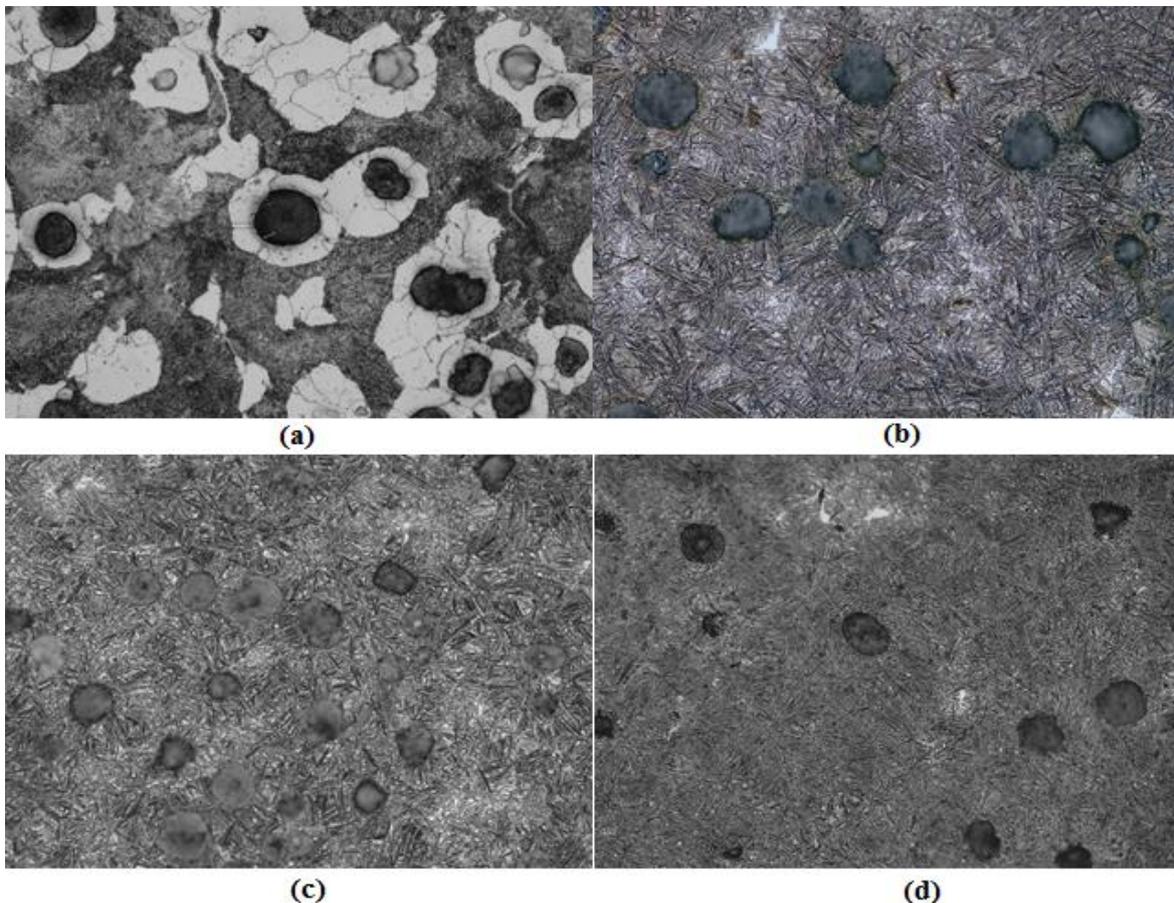


Figure 5. SEM micrographs of ductile iron at (a) as-cast and austempering at (b) 320°C, (c) 300°C e (d) 280°C.

4. CONCLUSION

From the results obtained in this work the following conclusions can be drawn:

- Mechanical properties of the alloy, such as the ultimate strength and the yield strength increase considerable after the austempering heat treatments;
- It was not observed a correlation between fatigue strength for 10^6 cycles and the ultimate strength for the austempered specimens;
- Analysis of the S-N data using the Basquim equation has shown that the alloy austempered at 280°C presented the best properties for lower cycle region of S-N curve, while the alloy austempered at 320°C presented best behavior for the high cycle region of S-N curve

5. ACKNOWLEDGMENTS

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