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INFLUENCE OF ALLOYING ELEMENTS Cu-Ni-Mo ON THE MECHANICAL PROPERTIES AND AUSTEMPERABILITY OF THE ADI[1]

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Abstract

ADI is the most recent development in the nodular iron family. With the austempering treatment, a unique microstructure named ausferrite is produced. This microstructure provides high mechanical strength combined with ductility, toughness and good fatigue and wear resistances. The aim of this work is to study the effect of alloying elements Cu, Ni and Mo on the mechanical properties and austemperability of the ADI. The addition of Mo decreased mechanical strength and toughness but increased both the wear resistance and austemperability.

Key words: Austempering; ADI; Alloying elements; Mechanical properties; Wear.

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1 INTRODUCTION

Austempered Ductile Iron (ADI) is obtained through the austempering treatment in the temperature range of 230 to 400ºC, usually of nodular cast iron with pearlitic matrix. Among all the nodular classes, the austempered are those with the best combination of mechanical strength, toughness, fatigue and wear resistances.

The chemical composition of the austempered nodular cast iron is similar to that conventional nodular cast iron. Thicker parts are made with introduction of alloying elements such as Cu, Ni and Mo individually or combined. These elements are added to increase the alloy austemperability, ie to prevent the perlite formation during cooling from the austenitizing temperature to the austempering temperature.[1-3]

The term used to denominate the ADI microstructure is ausferrite, consisting only of acicular ferrite and high-carbon stable austenite, being subdivided into higher ausferrite (for austempering temperatures higher than 330 ˚ C) and lower ausferrite (for austempering temperatures lower than 330 ˚ C). The ASTM A 897 standard names this structure as "acicular ferrite and austenite”.

The heat treatment cycle of the austempered ductile iron is composed primarily by heating above the critical temperature, where austenitisation starts. The austenitizing temperature is a function of the alloy chemical composition.[4,5] The elements that most influences the austenitizing temperature are Si, Mo and Mn. Si and Mo increase the required austenitizing temperature, while Mn decreases it.[6] Usually the austenitizing temperature is between 825 and 950 º C. The part should remain at this temperature long enough to saturate the austenite with carbon until the equilibrium is reached.

The austenitizing temperature determines the maximum carbon content that can be dissolved in austenite. The carbon dissolved in austenite in turn, influences the transformation kinetics during the austempering treatment.[4]

In austempered ductile irons, as greater the amount of acicular ferrite in the structure, increases the mechanical strength and lowers the ductility. For high austempering temperatures (350 - 400 º C) the smaller amount of acicular ferrite and the larger amount of the stable austenite, implies in high toughness and ductility, but with lower strength and hardness.[6]

ZIMBA et al.[8] verified that the ADI abrasive wear resistance is much superior to the nodular cast iron in as-cast state, and regarding to steels with equivalent hardness, the ADI showed twice in wear resistance. In his tests, the surface transformation of the retained austenite into martensite occurred and this phenomenon increased the ADI superficial hardness and wear resistance.[9,10] Because this is only a superficial transformation, the material toughness is not lost. Therefore, the ADI displays a rare combination of high strength, mechanical toughness and wear resistance.

Due the advantages offered by this class of material, its use becomes very interesting in several industry applications, and so does R&D intending to improve these materials properties.

In this work the effect of the alloying elements Cu, Ni and Mo on the ADI mechanical properties and austemperability was studied.

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2 MATERIALS AND METHODS

The furnace charge for the melt was composed of 20% of steel scrap, 40% of pig iron and 1.6% Fe-Si (inoculant). Graphite granules (carburetant) were added in enough quantity to correct silicon. In the ladle, 1.2% Mg-Ca was added for the formation of graphite nodules. The rest of load consisted of foundry scrap (castings refugees and hot top). An Inductoterm Induction furnace was used, with set temperature of 1500 º C. The pouring to obtain the samples was made at around 1360 º C in sand molds.

Cylindrical bars of nodular cast iron with different diameters were produced with three different chemical compositions:

- Nodular cast iron Ø2” bar alloyed with Cu
- Nodular cast iron Ø3” bar alloyed with Cu-Ni
- Nodular cast iron Ø4” bar alloyed with Cu-Ni-Mo

To analyze the influence of the alloying elements Cu, Ni and Mo, the amount of Cu was fixed in the Ø2”, Ø3” e Ø4” bars and the Ni amount on the bars Ø3” ~~e~~ and Ø4”. The samples chemical compositions were obtained by spectrometry (Table 1), in samples removed from the same run bar. The last line in table shows the materials equivalent carbon (EC) according to the equation:

$$E.C. = \%C + \frac{\%Si}{3} + \frac{\%P}{3} \qquad \text{(Eq. 01)}$$

Table 1. Average chemical compositions of produced nodular cast irons (Weight %)

	Bar Cu	Bar Cu-Ni	Bar Cu-Ni-Mo
%C	3,70	3,82	3,80
%Si	2,73	2,67	2,55
%Mn	0,21	0,20	0,26
%Cu	0,71	0,72	0,72
%Ni	-	1,22	1,62
%Mo	-	-	0,25
E.C. [%]	4,61	4,71	4,65

To manufacture the specimens, the bars were longitudinally cut as shown in Figure 1 and the samples were removed from the half-radius position.

Initially, specimens for tensile test (according to ASTM E8M), Charpy tests (according to ASTM E23) and for microwear tests were machined, being 1/3 of these for each of the chemical compositions used (3 altogether), in order to verify the Cu-Ni-Mo alloying elements influences on the ADI mechanical properties. In the case of the as-cast material alloyed with Cu-Ni-Mo, an annealing treatment was carried out to reduce the material hardness, to facilitate the specimens machining.

The samples were subjected to dry sliding fixed ball wear tests and the worn volume was calculated from the crater diameter.[11] The tests parameters were:

- AISI 52100 ball diameter: 25,4 mm.
- Load: 2,46 N.
- Ball rotation speed: 350 RPM.

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- Tests periods: 10, 15, 20 and 30 min corresponding to the traveled distances of 279; 419; 559 and 838 m.
- Samples roughness range: 2 to 5 µm.

Figure 1. Schematic representation of the "Sliced" cylindrical bar used for the specimens manufacture.

Samples austenitizing was carried out in an Industrial furnace at 890 °C for a period of 2 hours to ensure the complete structure homogenization. The austempering was carried out at 360 °C, during a period of 3 hours, in a neutral salt bath. The microstructural differences as function of the samples radius were analyzed by optical microscopy.

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3 RESULTS AND DISCUSSION

3.1 Austemperability Analysis

Figures 2 to 4 shows the ADIs microstructure variations as function of the bar radius positions.

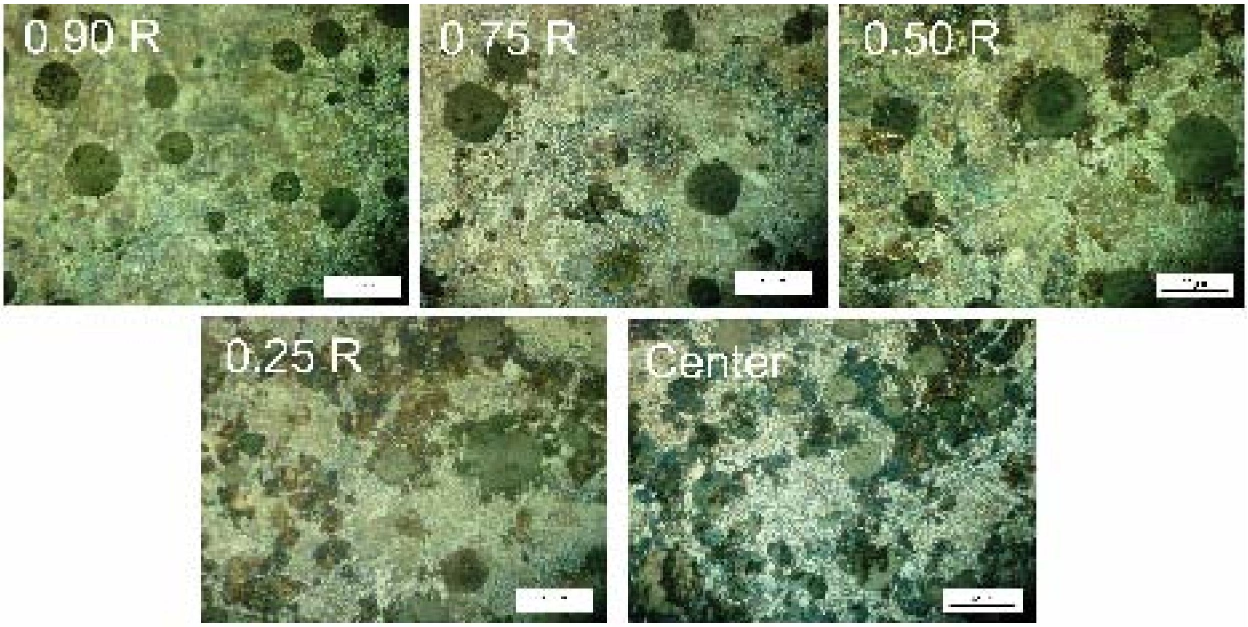

Figure 2. Ø2" ADI bar alloyed with Cu, microstructure variation as function of radius.

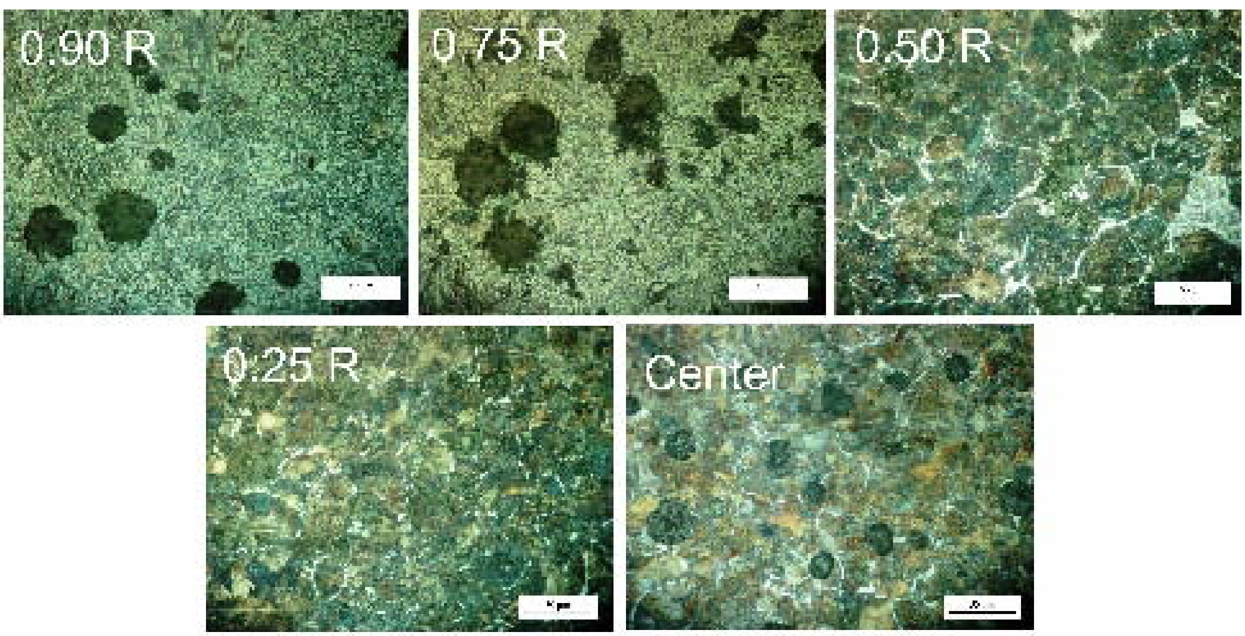

Figure 3. Ø3" ADI bar alloyed with Cu-Ni, microstructure variation as function of radius.

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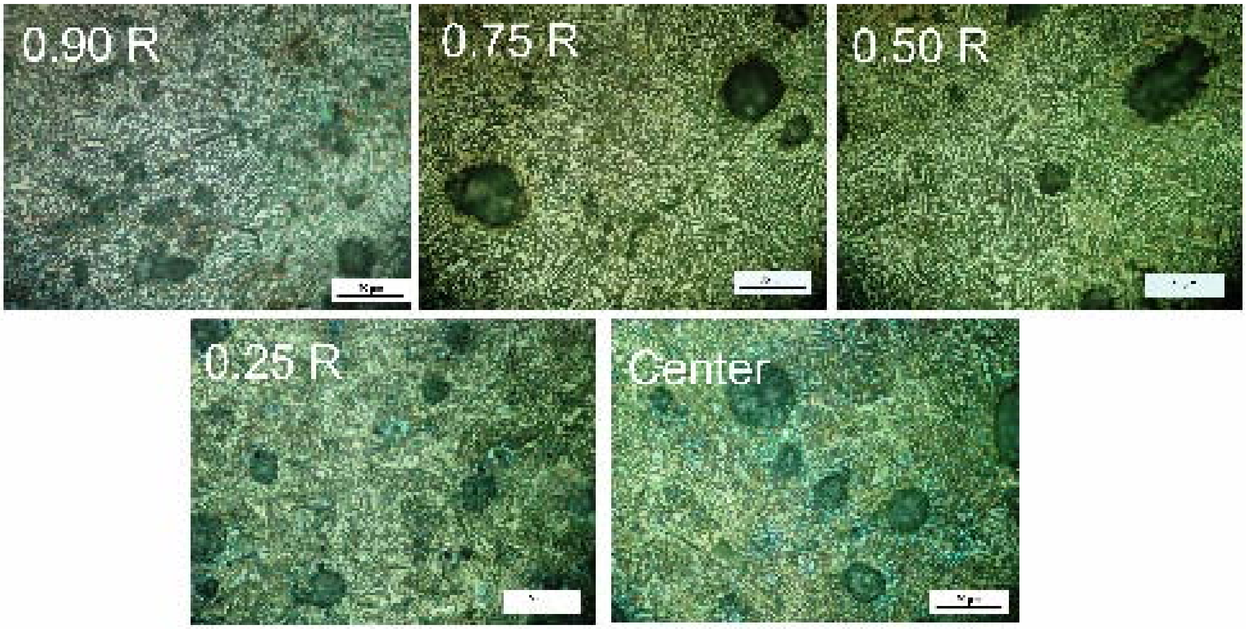

Figure 4. Ø4" ADI bar alloyed with Cu-Ni-Mo, microstructure variation as function of radius.

Comparing microstructural analysis presented in Figures 2 to 4 with the results obtained with the VOIGT LOPER equation[12] - Equation 2, which lists the "critical diameter" of an austempered rod with austempering temperature and chemical composition of the ADI. This critical diameter expresses the ADI austemperability, ie the largest bar diameter to provide completely ausferrite structure, without the presence of pearlite or other unwanted structures, with a determined treatment condition. Table 2 shows the values calculated by Equation 2.

$$\begin{aligned} CD &= 124 * C_{\gamma}^{\circ} + 27(\%Si) + 22(\%Mn) + 16(\%Ni) - 25(\%Mo) - 1{,}68 * 10^{-4}(Ta)^2 \\ &+ 12(\%Cu)(\%Ni) + 62(\%Cu)(\%Mo) + 88(\%Ni)(\%Mo) + 11(\%Mn)(\%Cu) \\ &+ 127(\%Mn)(\%Mo) - 20(\%Mn)(\%Ni) - 137 \end{aligned} \quad \text{(Eq. 02)}$$

Where:

CD = Bar critical diameter [mm];
C˚γ = Amount of dissolved carbon in austenite [%] – Eq. 01.; and
Ta = Austempering temperature [˚C].

Table 2. Austempered bars theoretical critical diameter

Material	Austempered bar Ø [mm]	% C˚γ	CD [mm]
Ø2" – ADI-Cu	46	0,705	9
Ø3" – ADI-Cu-Ni	70	0,715	33
Ø4" – ADI-Cu-Ni-Mo	94	0,736	89

By analyzing the ADI-Cu bar (Ø46mm) microstructure, it can be seen, around 0.60. R, the presence of others constituents in addition to ausferrite, i.e. the sample was austempered only until approximately 9mm. This was expected, since the bar diameter is much larger than the critical diameter calculated by the VOIGT LOPER equation.

On the ADI-Cu-Ni bar (Ø70mm) in 0.50 R position there is practically no vestige of ausferrite. The presence of other constituents begins to be noticed around 0.65. R, i.e. the sample was austempered only around a depth of 12mm. It can be also observed the ferrite presence in grain boundary (pro-eutectoid ferrite). This behavior regarding autemperability was expected too since the bar diameter is much larger than the critical diameter calculated by the VOIGT LOPER equation.

The ADI-Cu-Ni-Mo bar (Ø94mm) was austempered all way to the center, proving the ADI austemperability VOIGH LOPER[12] equation efficiency. Although the bar diameter is slightly higher than the calculated critical diameter, only ausferrite was found on the center of this rod.

3.2. Mechanical Properties Analysis

Table 3 shows the alloyed ADIs and cast irons (CI) mechanical properties.

Sample	Tensile Strength [MPa]	Yield Strength [MPa]	Elongation [%]	Hardness [HB]	Impact [J]
ADI-Cu	1105	813	7,3	363	154
As-cast-Cu	653	403	1,9	239	22
ADI-Cu-Ni	1044	778	5,4	342	135
As-cast-Cu-Ni	747	434	1,8	245	26
ADI-Cu-Ni-Mo	894	626	3,8	323	54
As-cast-Cu-Ni-Mo	595	432	2,0	210*	18

* *The bar was annealed at 700 ˚ C for 5 hours. The as-casting material hardness was 330 HB.*

As can be seen in Table 3 and Figure 5, the austempering treatments performed in nodular cast irons improved significantly the mechanical properties compared with the as-casting materials. The tensile strength was 60% higher than the as-casting for the ADI alloyed with Cu and above 35% for the other alloys. In all cases a significant increase in elongation and absorbed impact energy occurred after the austempering heat treatment, even with the increase in the mechanical strength, showing the great effectiveness of the austempering process applied in nodular cast iron, a fact usually not observed in steels.

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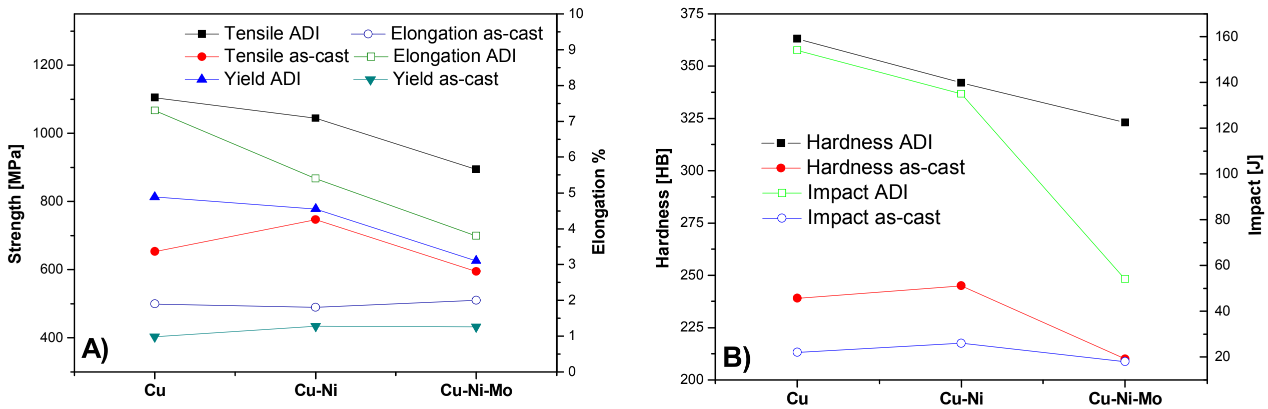

Figure 5. Mechanical properties as a function of alloying elements.

The lowest mechanical strength in the as-cast Cu-Ni-Mo material is due to the annealing process carried out in order to reduce the material hardness to facilitate the specimens machining. There is no relation between the annealing and the lowest mechanical properties values in the ADI-Cu-Ni-Mo, because the austenitizing was sufficient to provide the carbon saturation in austenite, ensuring the ausferrite structure after austempering process. This same mechanical properties behavior, ductility and toughness in ADI alloyed with Ni-Mo was also reported by Elsayed (2008). The presence of Mo can usually lead to segregation, responsible by a decrease in strength, ductility and toughness.

3.3. Microwear Evaluation

Figure 6 shows the wear behavior of the austempered and as-cast samples.

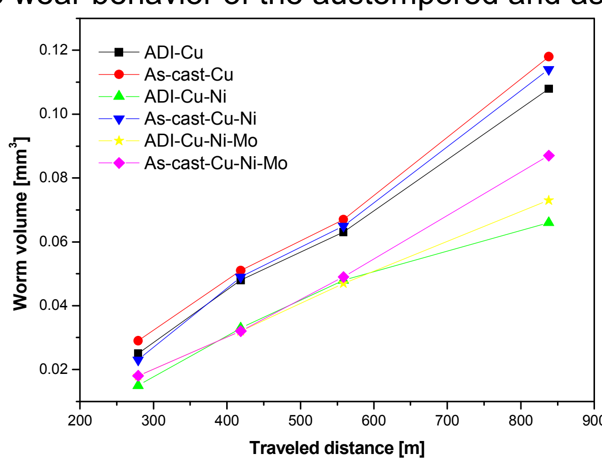

Figure 6. Wear behavior of the austempered and un-treated samples.

As can be seem in Figure 6, in all cases after the austempering treatment an increase in the wear resistance occurred, but the most significant difference occurred in the sample alloyed with Cu-Ni, being the ADI-Cu-Ni the one that showed the lowest wear, followed by the ADI-Cu-Ni-Mo, indicating that the hardness was not the most relevant factor in relation to wear in austempered samples.

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The ADI alloyed with Cu showed higher mass losses than the ADI alloyed with Cu-Ni or Cu-Ni-Mo. It is presumable that the alloying elements addition alters the carbon diffusion rate to stabilize the austenite, and these being unstable, can become martensite by transformation induced plastiticity (TRIP), which is beneficial for wear resistance.[7,13,14,8]

4 CONCLUSIONS

In the austemperability analysis the ADI-Cu-Ni-Mo Ø94mm bar showed only the ausferrite presence in the center, confirming the VOIGT LOPER[12] equation efficiency to calculate the ADI critical diameter (CD).

The Mo influence in austemperability was significant, although its use may cause alloying elements segregation, reducing strength, ductility and toughness.

The austempered ductile irons presented higher ductility and toughness than the as-cast materials, even with a significant increase in tensile strength, showing the austempering process great effectiveness when applied in nodular cast iron.

Regarding to wear resistance, ADI alloyed with Cu showed higher mass losses than the ADIs alloyed with Cu-Ni or Cu-Ni-Mo, but in all case after austempering, the wear behavior was improved.

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