Influence of the chemical composition on the ausferritic transformation in carbide-free bainitic cast steel

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Abstract. This work focuses on the study of the solid state transformations that take place during the austempering of high silicon carbide-free bainitic cast steels with different chemical composition. In order to get this objective three cast steel melts with different chemical compositions were produced, evaluating the influence of Cr, Mn, Ni, Al and Co. For each of these steels, samples were subjected to an austempering heat treatment at 340 °C varying the austempering time from 5 sec to 120 sec. The results show that small regions of free ferrite were obtained during continuous cooling from the austempering time (5 sec), the presence of a small fraction of ausferrite was observed. Austempering for 60 sec showed a larger amount of ausferrite. However, the ausferritic reaction is incomplete, and some martensite also was present, mainly located in last to freeze (LTF) zones. After an austempering of 120 sec, a fully ausferritic matrix was obtained. The addition of Cr and Mo avoided the initial precipitation of free ferrite, and lowered the isothermal transformation kinetics. On the other hand the use of Al and Co increase the presence of ferrite formed during continuous cooling and accelerates the kinetics of the ausferritic reaction.

Introduction

In recent decades there have been significant advances in the development of medium-carbon steel with carbide-free bainitic microstructure, also called "ausferritic steel". This type of steel has a microstructure composed by a mixture of ferrite and high carbon retained austenite. Such microstructure is obtained by performing austempering heat treatments similar to those used in the production of conventional bainitic steels, reaching a material with excellent mechanical properties compared with other more expensive steels [1-9]. The chemical composition of the ausferritic steel includes the use of inexpensive alloying elements, such as silicon ($\approx 1.5-2$ %), that inhibit the precipitation of carbides, stabilizing the austenite at room temperature by increasing its carbon content. The successful development of these steels demands a better knowledge and understanding of the bainitic transformation mechanism.

The mechanical characterization of this novel microstructure has revealed high combination of strength and toughness, with high ductility [1-7]. Austempering treatment at high temperature promotes high elongation until failure and toughness, while the use of lower temperatures promotes high tensile strength, yield strength and hardness [1-10]. Depending on the heat treatment cycles used, the mechanical testing has showed values of tensile strength ranging from 1.5 to 2.2 GPa, yield stress ranging from 1.0 and 1.8 GPa, hardness in the range of 500-700 HV, elongation until

failure between 5 and 30%, and fracture toughness values up to 130 MPa m^{1/2}. As regards fatigue properties, fatigue limit values ranging from 600 MPa to 1.5 GPa have been reported, depending on the austempering temperature [1-9]. These excellent mechanical properties are comparable to those of Maraging or TRIP steels, which are approximately 5-7 times more expensive [5-8]. Fig. 1 shows the mechanical properties of this new kind of steel and other advanced steels.



Fig. 1: Mechanical properties range of carbide free bainitic steels and other advanced steels.

Many works reported in the literature related to carbide-free bainitic steels are centered on the determination of their mechanical and wear properties depending on the chemical composition and heat treatment variables. However, all these studies are conducted on steels that have previously undergone different thermal or thermomechanical heat treatments, such as homogenization heat treatment, rolling or forging. However, many steel parts applicable to the automotive, mining or oil industries can be obtained through the melting and casting technique (crankshafts, camshafts, pump bodies, suspension parts, etc.), and these pieces have different geometries and varying thicknesses. It is widely recognized that the mechanical properties of castings differ from those obtained on rolled or forged parts of the same chemical composition; therefore in order to encourage the industrial application of these steels in cast parts it is of great interest to study the solidification process, chemical segregation and mechanical properties.

In this work the solid state transformations that occur during the austempering stage in carbidefree bainitic cast steels, for different chemical compositions, were studied. In order to reach this objective three cast steel melts with different chemical compositions were produced, evaluating the influence of Cr, Mn, Al, Ni and Co. For each of these steels, samples were obtained and subjected to an austempering heat treatment for different times, evaluating the influence of these variables on the final microstructure.

Experimental

Melts and samples. Three different steel melts were prepared using a medium frequency induction furnace. Steel scrap and foundry returns were used as raw materials. The chemical compositions were chosen so as to evaluate the influence of Cr, Mn, Al and Co on the ausferritic transformation. The melts were poured in 25 mm-thick Keel-block-shaped sand molds. The chemical composition was determined by using a Baird DV6 spectrometer. Round samples of 10 mm diameter and 30 mm length were cut from the Keel-blocks and used to prepare test specimens.

Thermal cycles performed to study the ausferritic transformation. Samples from each steel were heat treated according the cycle shown in Fig. 2. Initially all sets of samples were completely austenitised by holding above the A_{C3} temperature, at 900°C for 1 hour, then they were rapidly transferred to a salt bath held at a temperature of 340°C for austempering. Finally, the samples were removed from the salt bath, after different time intervals, and water quenched. The sets were

removed from the salt bath at: 5 sec, 30 sec, 60 sec and 120 sec. After heat treatments, the microstructures were characterized by using an optical microscope and the Image Pro Plus software. The preparation of the metallographic sample was carried out by using standard techniques for cutting, grinding and polishing. Etching was performed with 2 % Nital. The hardness was measured using Rockwell C scale.



Fig. 2: Heat treatment cycles used to study the ausferritic reaction.

X-Ray Diffraction Analysis. The amount of retained austenite and ferrite present in the microstructure of the samples austempered at 340 °C were evaluated by X-ray diffraction (XRD) analysis by means of a Panalytical X'pert Pro diffractometer, using a Cu target and graphite monocromator, operating at 40 kV and 40 mA and scanning in the range of $30^{\circ} < \alpha < 90^{\circ}$ at a speed of 1 deg/min. The volume fraction of ferrite and retained austenite were then determined using the integrated intensities of the {111-200-220-311} planes of austenite and the {110-200-211} planes of ferrite.

Results and discussion

The chemical compositions of the steels are listed in Table 1. Besides Si, these medium carbon steels include Mn, Cr, Mo, Al, Ni and Co as alloying elements in order to evaluate the influence of these elements on the ausferritic reaction kinetics during the austempering stage. As shown in Table 1, Steel 1 was taken as a reference of unalloyed steel and its chemical composition corresponds with SAE 9260 steel. Steel 2 was alloyed with Cr, Ni and Mo to improve hardenability [3-5], while Al and Co were added to Steel 3 to accelerate the ausferritic reaction kinetics [5-8]. For the three steels under study, the as-cast microstructure was mainly pearlitic, with free ferrite as a second phase located preferentially at the grain boundaries of the prior austenite. Fig. 3 shows the as-cast microstructures for steels 1, 2 and 3.

STEEL	%C	%Si	%Mn	%Cr	%Ni	%Mo	%Al	%Co	%S	%P
1	0.60	2.13	0.60						0.0076	0.017
2	0.53	2.06	0.59	0.52	0.49	0.53			0.0048	0.010
3	0.57	2.06	0.58	0.59	0.56	0.53	0.61	0.20	0.0095	0.022

Table 1. Chemical compositions of the steels (weight %).



Fig. 3: Microstructure of Steel 1 (a), Steel 2 (b) and Steel 3 (c), as-cast condition.

Fig. 4 shows the microstructure of samples obtained from Steel 1 austempered at 340 °C during 5 sec, 60 sec and 120 sec. When the austempering time is 5 sec (Fig. 4a) a predominantly martensitic microstructure with small evidence of ausferritic transformation is found. In addition, the presence of small regions of free ferrite in last to freeze zones (LTF), indicated by an arrow in Fig. 4b, was observed. The free ferrite was formed during cooling from austenitising temperature to austempering temperature. The formation of this ferrite is attributed at the low hardenability of the Steel 1, although the shape of the precipitates is somehow unexpected. This will be analyzed in future research. The sample austempered for 60 sec, Fig. 4c, displays higher amount of ausferrite. However, the ausferritic reaction is incomplete, and some martensite is present, located mainly at LTF zones. After austempering for 120 sec, a fully ausferritic matrix is obtained (Fig. 4d).



Fig. 4: Microstructures of the Steel 1 austempered at 340 °C during 5 sec (a and b), 60 sec (c) and 120 sec (d).

Phases present in the microstructures described above were verified by XRD. The diffraction diagrams for the three austempering times analyzed are shown in Fig. 5. The amount of retained austenite measured by XRD in the sample austempered during 5 sec was approximately 8.5% and its hardness was 62 HRC. On the other hand, the amount of retained austenite for samples austempered for 60 sec and 120 sec were 10.6 % and 13 %, respectively while the hardness

measured in the same samples were 55 and 50 HRC, respectively. These results clearly show that as the austempering time increases, the amount of retained austenite rises attaining a maximum value for the Steel 1 of 13%.



The microstructural analysis of samples from Steel 2 austempered at 340 °C verified the expected increment of the hardenability of this alloy caused by the addition of Cr and Mo [6-9], since all the samples are free from free ferrite. The amount of austenite on the sample austempered at 340 °C for 5 sec is 1.7%, lower than the austenite content measured in sample from Steel 1. The examination of the microstructure of the samples austempered at 340°C for 60 and 120 sec (Fig. 6) reveals the presence of lower amounts of ausferrite than those of Steel 1. These results indicate that Steel 2 has slower ausferritic reaction kinetics as compared to Steel 1.



Fig. 6: Microstructures of the Steel 2 austempered at 340 °C during 60 sec (a) and 120 sec (b).

Fig. 7 shows the microstructures corresponding to Steel 3, austempered at 60 sec (Fig. 7-a) and 120 sec (Fig. 7-b). Under identical heat treatment cycles than Steel 1 and 2, Steel 3 shows free ferrite in all the samples evaluated, and also shows faster ausferritic reaction kinetics than Steel 2. The ferrite is located in LTF and interdendritic zones, possibly due to the segregation of Al and Co.



Fig. 7: Microstructures of the Steel 3 austempered at 340 °C during 60 sec (a) and 120 sec (b).

Fig. 8 shows the change in the amount of retained austenite as a function of the austempering time for the steels investigated. Hardness values are also given in the figure. For the time range investigated the amount of retained austenite increases with the austempering time for all steels. On the other hand, the hardness decreases when the austempering time is increased. The amount of retained austenite is proportional to the amount of ausferrite present in the microstructure. As the amount of ausferrite increases, the amount of martensite decreases, causing the observed decrease in hardness. For all the austempering times investigated Steel 2, alloyed with Cr, Ni and Mo that increase its hardenability [7-10], shows a much smaller amount of retained austenite than Steel 1. This steel showed a slower kinetic of the ausferritic transformation. On the other hand, Steel 3 exhibited higher amount of retained austenite than Steel 2, but smaller than Steel 1. This change in the kinetics of transformation is caused by the inclusion of Co and Al that caused a decrease in the hardenability [9, 11-13].



Fig. 8: Amount of retained austenite and hardness as a function of the steel and austempering time.

The results of the steels studied show that the ausferritic transformation at 340°C is very fast; taking only a few seconds to obtain a fully ausferritic matrix in all cases. However, austempering at lower temperatures should exhibit important difference in the kinetic reaction. Future work will be addressed to examine this matter.

Conclusions

This work studies the advance of the ausferritic transformation of high silicon carbide-free bainitic cast steels of different chemical compositions. The results show that the chemical composition of the steel has a strong effect on the kinetics of the ausferritic transformation. The results show that the kinetics of the ausferritic transformation at 340 °C in unalloyed and low alloy high silicon cast steels is very fast. Only a few seconds are needed to obtain a fully ausferritic matrix in all cases. XRD analysis showed that the amount of retained austenite after austempering of unalloyed steel grows rapidly from 8 to 13% as the austempering time goes from 5 to 120 seconds. Holding for just 120 seconds allowed to obtain a fully ausferritic matrix. Small regions of free ferrite were obtained during continuous cooling from the austenitising to the austempering temperatures in the un-alloyed high silicon cast steels. The addition of Cr, Ni and Mo to the chemical composition increased the hardenability and avoided the precipitation of free ferrite during cooling. However, the ausferritic kinetic reaction was delayed. On the other hand, as Al and Co was also added, the hardenability decreases and the free ferrite precipitation take place.

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