Key Engineering Materials Vol. 457 (2011) pp 187-192
© (2011) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/KEM.457.187

Advances in the Development of Carbidic ADI

Laino Sebastián[1,a], Sikora Jorge[2,b] and Dommarco Ricardo C.[1,c]

[1] Tribology Group – Faculty of Engineering

[2] Metallurgy Division – INTEMA

National University of Mar del Plata – CONICET

Av. J. B. Justo 4302, B7608FDQ – Mar del Plata – ARGENTINA

[a]slaino@fi.mdp.edu.ar, [b]jsikora@fi.mdp.edu.ar, [c]dommarco@fi.mdp.edu.ar

Keywords: carbidic ADI, abrasion severity, field trials, scratch test, impact toughness.

Abstract. Carbidic ADI (CADI) is a new type of Austempered Ductile Iron containing free carbides in the microstructure, providing a particular combination of wear resistance and impact toughness. In this work, four CADI variants were evaluated, in which carbides were promoted by alloying with chromium.

Tests performed under the low stress abrasion condition imposed by the ASTM G65 standard show that CADI can increase the wear resistance up to ~100 % when compared with conventional ADI austempered at the same temperature.

The carbide content must be higher than ~10 % to promote a considerable reinforcing effect. However, at this carbide content level, the impact toughness varies between ~7 and ~11 J/cm^2 for unnotched samples. These values are much lower than those of conventional ADI, but higher than those of other abrasion resistant materials, like white irons.

Some CADI variants were also evaluated in field tests, producing abrasion under either low stress or high stress conditions. For this purpose, two CADI prototype parts were studied: screw segments for animal food extruders (low stress abrasion) and wheel loader bucket edges (high stress abrasion).

The results gathered showed that CADI behaves satisfactorily under low stress abrasion, but the performance is not so good under high stress conditions. To analyze the differences in the abrasion response, scratch tests were performed in order to evaluate the interaction between the abrasive tip and the microstructure.

Introduction

Austempered Ductile Iron (ADI) has long been recognized for its high mechanical properties, over 1600 MPa ultimate tensile strength and 110 J impact toughness for the 1600-1300-01 and 750-500-11 grades, respectively, pursuant to the ASTM A897M-06 standard. These characteristics have enabled ADI to replace forged steels in many applications. The optimum performance of ADI under different wear mechanisms such as rolling contact fatigue, adhesion and abrasion has also been widely acknowledged [1-4]. Additionally, ADI variants have proved to behave in a different manner under abrasive conditions, depending on the tribosystem (two- or three-body abrasion, low or high stress abrasion), though generally ensuring a good performance in service, provided that the heat treatment parameters are properly selected [3,4].

On the other hand, it is common knowledge that it is possible to enhance the abrasion resistance of a material by incorporating a reinforcing phase or hard particles [1].

During recent years, some studies have been conducted to develop a chromium alloyed abrasion resistant variant of ADI, containing carbides with variable chemical composition, morphology, size and quantity, with a view to obtain greater impact toughness than that of other wear resistant materials. This is how Carbidic ADI (CADI) arose. CADI's microstructure is identical to that of ADI (graphite nodules immersed in an ausferritic matrix) besides the presence of dispersed carbides. The first studies on CADI were undertaken by researchers from the American company Applied

Process who obtained and characterized two variants of this material, particularly evaluating the laboratory abrasion resistance and comparing the results with those corresponding to traditional abrasion resistant materials [1,2].

There are several ways to introduce carbides in ductile iron. A reduction in the quantity of graphitizing elements (in particular Si) is known to promote the precipitation of ledeburitic carbides during solidification. This methodology may be combined with a second option given by the high undercooling resulting from the use of a chill in the mould. A third option is to alloy the melt with carbide stabilizing elements, such as Cr, Mo or Ti [6,7], which strongly reduce the interval between stable and metastable eutectic temperatures leading to total or partial solidification according to the metastable diagram [1].

As demonstrated for ADI, CADI's wear resistance is strongly linked to the tribosystem [1]. This is of particular concern when selecting a material for a given application: since most abrasion resistance reference values are gathered from laboratory wear tests, it is likely that the tribosystem used does not properly simulate the actual field conditions.

This work deals with different CADI variants, in which carbide precipitation was obtained by alloying with chromium contents between 0.5 and 2.5 wt.% [1,2]. CADI's wear resistance was evaluated under different abrasion conditions, not only in laboratory tests but also in two different field trials. Additionally, in order to study the abrasion micro-mechanism at different load levels, scratch tests were conducted to assess the interaction of an abrasive tip with CADI microstructure.

Experimental Procedure

The ductile iron heats used for the present work were obtained in a metal casting laboratory using a 55 kg capacity 3 kHz induction furnace and casting 180 x 225 x 25 mm plates in sand moulds. All heats were nodularized with Fe-Si-Mg (9 wt% Mg), inoculated with Fe-Si (75 wt% Si) and alloyed with small amounts of copper and nickel so as to ensure enough austemperability. The heats used to produce CADI were alloyed with Cr contents between 0,5 and 2,5 % to favor the precipitation of alloyed cementite $(Fe, Cr)_3C$. A ductile iron heat without Cr was also produced to obtain conventional ADI samples to be used as reference material for abrasion and impact tests.

CADI samples were obtained from all the heats alloyed with Cr after a heat treatment involving an austenitizing stage in a muffle at T_γ=900 ºC during t_γ=1 h, followed by an austempering step in a salt bath at different austempering temperatures (Ta) during ta=2 h, taking into account prior works by the authors. Sample identification was done as follows: C1 refers to heat 1 in the as cast condition, and A1-XXX refers to the same heat after austempering at XXX ºC.

Metallographic sample preparation for optical microscopy examination was conducted by using standard cutting and polishing techniques, and etching with 2% Nital.

The abrasion wear resistance of CADI variants was evaluated in the laboratory by means of the Dry Sand/Rubber Wheel Abrasion Test according to the ASTM G65 standard and applying procedure A. The Relative Wear Resistance index (*E)* was calculated as the ratio between the volume loss experienced by the ADI samples austempered at the same Ta as CADI, used as the reference material (ΔV_R), and the CADI samples (ΔV_S), as set forth in Eq. 1.

$$E = \frac{\Delta V_R}{\Delta V_S} \tag{1}$$

CADI's wear resistance was also evaluated by field trials in two different applications. One of them consisted of screws for animal food extruders, which are about 100 mm in diameter and 160 mm in length, produced in a 2.5 %Cr CADI variant and austempered at Ta=280 ºC. The other application consisted of wheel loader bucket protection segments, which dimensions are about 300 x 300 x 25 mm, produced in an industrial facility with 1.0 and 2.0 %Cr CADI variants and austempered at Ta=300 ºC.

The abrasion micro-mechanism was studied by conducting scratch tests. The scratches were obtained by sliding a Vickers indenter under two different loads, 1 N and 10 N. The scratches as well as the wear scars from the laboratory and field wear tests were analyzed by optical and scanning electron microscopy.

Impact toughness tests were carried out in agreement with the ASTM E23 standard using 10x10x55 mm specimens and an Amsler pendulum with an initial energy of 300 J (5 m/s impact speed). In view of the characteristics of the materials evaluated, unnotched samples were employed.

Results and Discussion

Chemical and microstructural characteristics of CADI. Table 1 lists the chemical compositions of the heats. It should be noted that all heats (except heat 5) were alloyed with chromium in order to promote partial solidification according to the Fe-C metastable diagram.

Table 1. Chemical composition for the different heats evaluated (weight %)

Heat	C	Si	S	P	Cu	Ni	Cr	CE*
1	3.35	3.09	0.039	0.042	0.67	0.58	2.59	4.38
2	3.40	3.00	0.015	0.039	0.65	0.56	2.04	4.40
3	3.29	3.28	0.019	0.035	0.60	0.59	1.45	4.38
4	3.18	3.38	0.016	0.037	0.63	0.61	0.84	4.31
5	3.40	3.34	0.019	0.035	0.62	0.63	0	4.51

* CE: carbon equivalent

The size and composition of carbides may vary, from low alloyed cementite to high alloyed carbides, depending on the chemical composition of the heat and the cooling rate imposed during solidification [1-3]. It was found that the carbides remaining stable after heat treatment were those strongly alloyed with chromium by the microsegregation effect in the last to freeze solidification zones. Unalloyed carbides were not stable, dissolving partially during the austenitizing step of the heat treatment. Carbide content after heat treatment ranged from 5 to 21 %, and its Cr content from 2 to 6 times the average %Cr of the alloy [9,10].

Two typical CADI microstructures are shown in Fig. 1, one with high Cr and carbide contents (Fig. 1-a) and the other with lower Cr and carbide contents (Fig. 1-b). Ausferritic matrices and graphite nodules can be also observed.

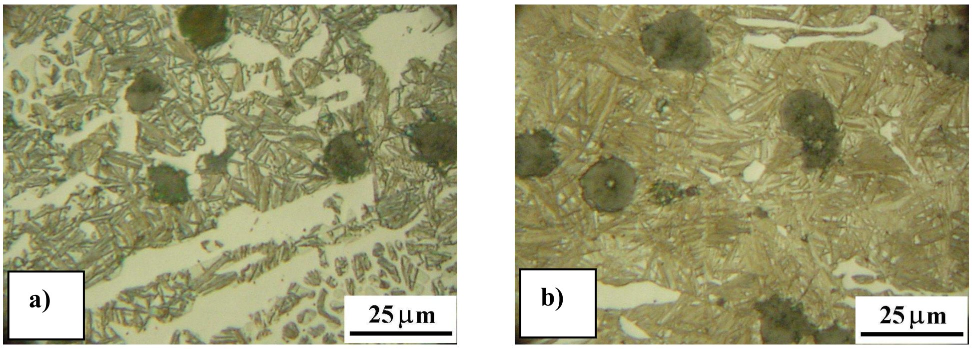

Figure 1. CADI microstructures with **a)** high carbide content (21 %, sample A1-260) and **b)** low carbide content (5 %, sample A4-260). (white areas= carbides, black areas= nodules, matrix=ausferrite)

Laboratory abrasion resistance tests. The results of the ASTM G65 wear tests are summarised in Fig. 2 and Fig. 3 for eutectic CADI samples (heats 1 to 4) austempered at 280 and 360 ºC, respectively. It can be seen that the presence of carbides increased the abrasion resistance up to

~100 % (E=1.99 for A1-360, Fig. 3) with respect to that of conventional ADI austempered at the same temperature. It is also observed that the reinforcing effect of carbides becomes significant for chromium contents higher than 1.5 %. Besides, the reinforcing effect of carbides was higher for the softer matrix (ADI 360).

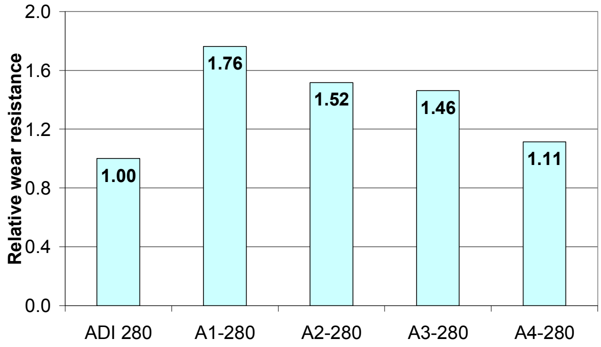

Figure 2. Relative wear resistance of eutectic CADI samples austempered at 280 ºC. Reference material ADI 280.

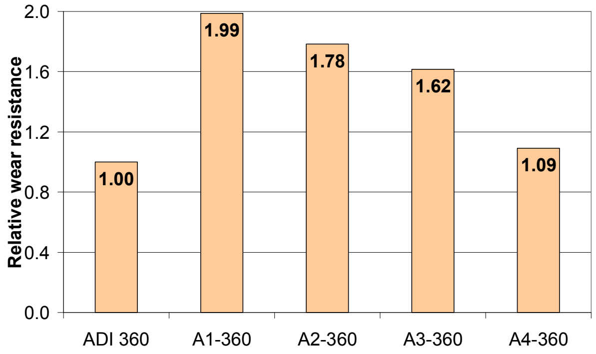

Figure 3. Relative wear resistance of eutectic CADI samples austempered at 360 ºC. Reference material ADI 360.

CADI field trials. Under the wear conditions imposed by the screws for animal food extruders, the abrasion resistance of CADI was higher than that of the original martensitic steel screws, which hardness is nearly 55 HRC. In this case, the wear resistance was evaluated in terms of the mass of food processed per millimeter lost by wear from the screw diameter. Average values of 280 t/mm for the CADI screws and of 228 t/mm for the steel screws were obtained.

On the other hand, under the wear conditions experienced by the wheel loader bucket protection segments, both CADI variants showed lower wear resistance than ADI, as depicted in Fig. 4. Besides, it should be pointed out that the lowest abrasion resistance was obtained for the variant with the highest chromium and carbide content and also the highest hardness.

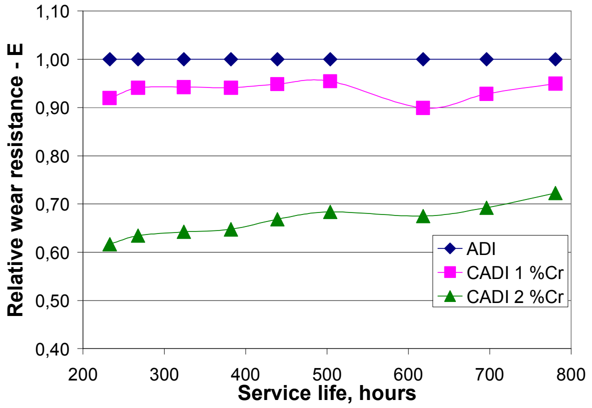

Figure 4. Relative wear resistance of CADI bucket edges vs. service time of the wheel loader. ADI segment used as reference material (E=1).

The extent of plastic deformation of the laboratory and field trials samples was evaluated by the wear scar analysis. The size of the furrows showed that the abrasiveness of the extruder screw as well as the laboratory tribosystems can be considered as a low stress type, whereas that of the bucket edges can be considered as a high stress type.

Fig. 5 shows SEM micrographs of CADI microstructures and different scratches obtained with 1 N (Fig. 5-a) and 10 N (Fig. 5-b) loads. As for the scratches obtained with a 1 N load, their width of nearly 20 µm mirrors that observed in the scratches present in the wear scar of the laboratory samples and extruder screws, and also the average carbide size in the CADI microstructure. On the other hand, the ~75 µm wide scratches obtained by using a 10 N load were comparable to those present in the worn surface of the bucket edges, although these were larger than the average carbide size.

Based on the results above, a possible explanation for the good CADI performance under low stress abrasion could be that the groove size is smaller than that of carbides, which are therefore able to play a reinforcing role [5]. Additionally, the reinforcing effect is related to the carbide content and spacing, as they are responsible for the decrease in the abrasive particle penetration depth, and thus in volume loss.

On the other hand, the unsatisfactory behavior of CADI under the high stress abrasion application evaluated can be related to the large scratch size compared to that of carbides. The scratch tests, together with previous work by Zum Gahr [5], showed that when the chip size is considerably larger than the average carbide size, carbides become less effective as reinforcing particles, since they are easily dug out as a part of the chip.

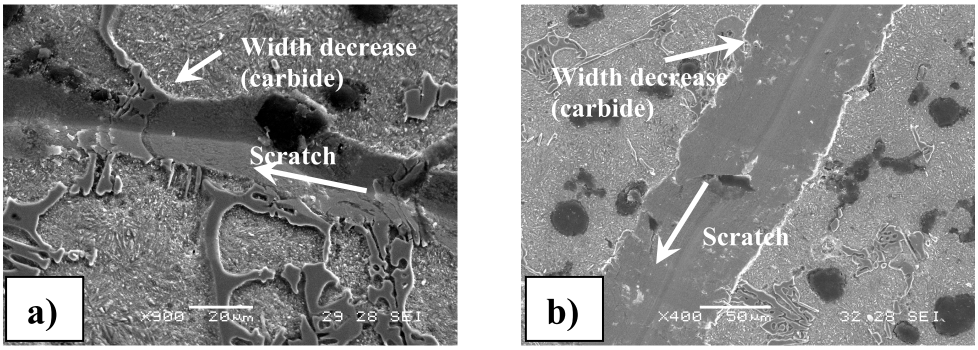

Figure 5. SEM micrographs of CADI microstructures and different scratches made with **a)** 1 N and **b)** 10 N load.

Impact toughness tests. Fig. 6 shows the results of the impact toughness tests for the CADI variants studied. As expected, the impact toughness decreased as the Cr content increased, but reached a quasi-steady level for Cr > 1.5% for the two austempering temperatures (A3-280 and A3-360 CADI variants). In order to compare with CADI samples, conventional ADI 280 and ADI 360 were also evaluated and impact toughness values of 101 and 138 J respectively were obtained. Even though the presence of carbides has a strong influence of decreasing the impact toughness, the ausferritic matrix still has an influence as shown by the higher values consistently obtained for the samples austempered at Ta=360 ºC.

Even when the impact toughness decreased from ~100-140 J/cm^2 for ADI to ~7 J/cm^2 for CADI variants with the highest carbide contents, it should be noted that these values are higher than those of competing high abrasion resistance alloys like white cast irons (up to ~3 J/cm^2 [7]).

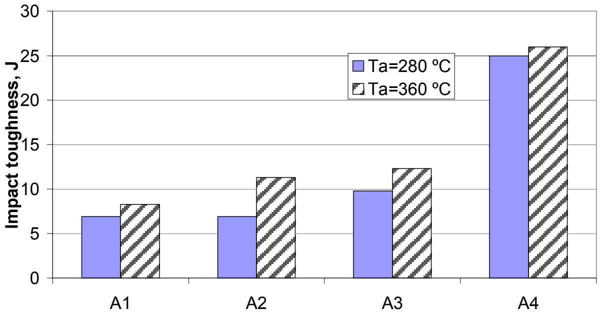

Figure 6. Impact toughness of eutectic CADI samples after austempering at two different temperatures.

Summary

The presence of carbides in the microstructure may increase the wear resistance up to 100% with respect to a conventional ADI austempered at the same temperature.

Based on the results obtained in the laboratory and field abrasion tests, it can be concluded that CADI behaves as a good abrasion resistance material under low stress abrasion conditions, though not when abrasion is of high stress type.

The good CADI performance under low stress abrasion could be explained by the relative sizes of grooves and carbides as well as by the carbide content and spacing, as these variables are responsible for the decrease in the abrasive particle penetration depth.

References

[1] R. Dommarco and J. Salvande: Wear, 254(2003), 230.

[2] L. Magalhães and J. Seabra: Wear, 215(1998), 237.

[3] R. Dommarco, I. Galarreta, H. Ortiz, P. David and G. Maglieri: Wear, 249(2001), 101.

[4] S. Laino, H. Ortiz, R. Dommarco: ISIJ International, 49(2009), no. 1, 132.

[5] K.H. Zum Gahr: Tribology International, 31(1998), no. 10, 587.

[6] J.R. Keough, K.L. Hayrynen: Ductile Iron News, 3(2000).

[7] K.L. Hayrynen, K.R. Brandenberg: American Foundry Society, 111(2003), 845.

[8] R.B. Gundlach, J.F. Janowak, S. Bechet and K. Rohrig: Materials Research Society Symposium Proceedings, Stockholm, Sweden, 34(1985), 251.

[9] S. Laino, J. Sikora and R. Dommarco: ISIJ International, 50(2010), no. 3, in press.

[10] S. Laino, J. Sikora and R. Dommarco: Wear, 265(2008), 1.

[11] S. Laino, J. Sikora and R. Dommarco: ISIJ International, 49(2009), no. 8, 1239.

[12] J. Lacaze, G. Torres Camacho and C. Bak: Int. J. Cast Met. Res., 16(2003), 167.

[13] L. Nastac and D.M. Stefanescu: Advanced Materials Research, 4-5(1997), 469.

[14] H. Zhao and B. Liu: ISIJ International, 41(2001), 986.