

# Wear Behavior of CADI Operating Under Different Tribosystems

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A new type of Austempered Ductile Iron (ADI) containing free carbides in its microstructure, called Carbide ADI (CADI), has been purposely designed for applications requiring high levels of abrasion resistance, but still keeping impact toughness. Nevertheless, wear resistance is strongly dependent on the tribosystem, and this is clearly noticed for the abrasive wear mechanism.

In earlier investigations, the authors used the low stress abrasion condition imposed by the ASTM G 65 standard for laboratory tests. Therefore, this study is intended to evaluate CADI wear resistance by means of field trials under different abrasion conditions.

Apart from the additional laboratory tests indicated by the ASTM G 65 standard, two CADI prototype parts were evaluated: screw segments for animal food extruders, whose abrasion severity is considered of low stress type (similar to that imposed in the laboratory), and wheel loader bucket edges, whose abrasion severity is considered of high stress type.

The results gathered have demonstrated that CADI behaves satisfactorily under low stress abrasion conditions, though performance is poor under high stress conditions. To justify the differences in wear behavior, the worn surfaces were studied by microscopy, and also scratch tests were performed in order to evaluate the interaction between the abrasive particles and the microstructure. It was found that the good performance is obtained when the groove size is smaller than the average carbide size, and that under this condition abrasion resistance increases with the increase in the carbide content and hardness. Contrarily, when the groove size is greater than that of carbides, the performance is impoverished with the increase in the carbide content.

KEY WORDS: CADI; abrasion severity; laboratory test; field trials; scratch test.

## 1. Introduction

Austempered Ductile Iron (ADI) has long been recognized for its high mechanical properties, over 1 600 MPa ultimate tensile strength and 110 J impact toughness for the 1600-1300-01 and 750-500-11 grades, respectively, pursuant to the ASTM A 897M-06 standard. These characteristics have enabled to replace forged steels with ADI 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.<sup>1–4)</sup> 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 ensuring, at all times, a good performance in service, provided heat treatment parameters are properly selected.<sup>3,4)</sup>

Some researchers<sup>5,6)</sup> have evaluated ADI abrasion resistance over a wide range of austempering temperatures ( $T_a \approx 220\text{--}360^\circ\text{C}$ ) in laboratory tests, and reported that the highest wear resistance is obtained from the hardest variants, *i.e.*, from the lowest  $T_a$ . Others<sup>7,8)</sup> have also noticed, in laboratory as well as in field wear tests, that the abrasion resistance of ADI soil ploughing tools increases as  $T_a$  decreases, though never exceeding the wear resistance of

hardfaced steels.

In a series of wear tests conducted in a pin-on-disk apparatus,<sup>9)</sup> it was observed that at similar hardness levels, ADI could exhibit greater abrasion resistance than quenched and tempered steels and other ductile cast irons. This behavior was mainly ascribed to the presence of austenite in the ADI matrix, which transforms into martensite as a result of the imposed strain.

The results obtained by Vélez and Tschiptschin in a series of scratch tests using the Uppsala pendulum technique, showed that, for the same  $T_a$ , wear resistance increases for the austempering time ( $t_a$ ) promoting the highest retained austenite content.<sup>10)</sup> Nevertheless, for different  $T_a$ , wear resistance increases with hardness, while austenite content diminishes. Zhou *et al.* also reported that ADI wear behavior is strongly associated with the austenite content, being also dependent on abrasion severity.<sup>11)</sup>

The aforementioned demonstrates that the wear resistance of ADI is strongly linked to the tribosystem. 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, being highly likely that the tribosystem used does not properly simulate the actual field conditions. Consequently, under ideal conditions, field trials should be conducted to assess the use of a given

material in a new application, still regarding its associated drawbacks such as higher cost, machine shut down, and sample tracking, among others.

The use of ADI for wheel loader bucket tips, for instance, has been evaluated in laboratory and field tests.<sup>3,4)</sup> Results have demonstrated that, while abrasion resistance increases with hardness in low stress laboratory tests, this trend reverses in high stress field trials. This behavior was attributed to the high strain capability of austenite along with the higher retained austenite content as Ta increases.

On the other side, it is common knowledge that it is possible to enhance the abrasion resistance of a material by incorporating a reinforcing phase or hard particles.<sup>12)</sup> With respect to the enhancement of cast irons abrasion resistance, Ceccarelli *et al.* carried out a study to explore the influence of carbide content in the abrasion resistance of ductile iron.<sup>13)</sup> To such an end, mottled cast iron with a pearlitic matrix containing graphite nodules and carbides was produced. Carbide precipitation was obtained by a copper chill in the mould. The results proved that a high carbide volume favors wear resistance, if compared to that of carbide free as-cast ductile iron, yet toughness diminishes to a large extent.

In another study by Giacchi *et al.*, a similar line of investigation was followed on gray cast iron.<sup>14)</sup> The results yielded very high abrasion resistance for a carbide content greater than ~40%. Nonetheless, when such content fell below this level and the graphite flakes changed from type D to type B, wear resistance also decreased significantly.

During the last years, some studies have been conducted to develop a chromium alloyed abrasion resistant variant of ADI (which is commonly not alloyed with chromium), containing carbides with variable chemical composition, morphology, size and quantity, with a view to sustaining greater impact toughness than that of other wear resistant materials. This is how Carbide ADI (CADI) arose. CADI's microstructure is identical to that of ADI (graphite nodules immersed in an ausferrite 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 its laboratory abrasion resistance (pin on disk and ASTM G 105 abrasion tests), and compared it to that of traditional abrasion resistant materials such as steels and cast irons.<sup>15,16)</sup>

Previous works by the authors<sup>17,18)</sup> have dealt with different CADI variants, in which carbide precipitation was obtained by alloying with chromium contents between 0.5 and 2.5 wt% in almost eutectic compositions, combined with a chill in the mould to vary the solidification rate. A hypoeutectic composition was also analyzed. It was found that the carbides remaining stable after heat treatment were those strongly alloyed with chromium by the microsegregation effect taking place at the last to freeze solidification zones. Unalloyed carbides (mainly present in the hypoeutectic variant), in turn, were not stable, dissolving partially during heat treatment. Carbide content after heat treatment ranged from 5 to 25%, and its Cr content from 2 to 6 times the average %Cr of the alloy.<sup>18)</sup> The results of the mechanical tests indicated that the presence of carbides increased the abrasion resistance up to ~200% with respect to that of

conventional ADI austempered at the same temperature.<sup>18)</sup> On the other hand, the impact toughness decreased from ~100–130 J/cm<sup>2</sup> for ADI to ~7 J/cm<sup>2</sup> for CADI variants with the highest carbide contents. Notwithstanding this, it should be considered that these values are higher than those of high abrasion resistance alloys like white cast irons (up to ~3 J/cm<sup>2</sup>).

Given the results above, it is believed that by exerting a good microstructure control based on the tribosystem, it is possible to obtain a high abrasion resistance material and thereby maintain good impact toughness. Then, the objective of this study was to evaluate CADI wear resistance under different abrasion conditions. To do so, not only laboratory tests but also two different field trials were carried out, evaluating the performance of different CADI variants. Additionally, scratch tests were conducted to assess the interaction of an abrasive with CADI microstructure.

## 2. Experimental Procedure

The heats used to obtain the laboratory wear test samples as well as the CADI prototype parts for field trials were produced in a metal casting laboratory, using a 55 kg capacity 3 kHz induction furnace and casting in sand molds. Steel scrap and foundry returns were used as charge materials. All heats were nodulized 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 chemical composition of all the evaluated alloys, measured by means of a spark emission optic spectrometer with a DV6 excitation source, is listed in **Table 1**.

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

Brinell hardness was measured in a bench tester using a 2.5 mm tungsten carbide ball and a 1875 N load (HBW<sub>2.5/187.5</sub>). In order to determine the hardness of the carbides and the matrix separately, microindentation tests were performed using a Vickers indenter and a 2 N load (HV<sub>200</sub>).

### 2.1. Laboratory Abrasion Tests

The abrasion wear resistance of some CADI variants austempered at two different temperatures (Ta=280 and 360°C) was evaluated by means of the “Dry Sand/Rubber Wheel Abrasion Test” according to the ASTM G 65 standard, and applying procedure A (test load 130 N, number of wheel revolutions 6000). The Relative Wear Resistance index (*E*) was calculated as the ratio between the volume loss experienced by the ADI samples (obtained from alloy C5, Table 1) austempered at the same Ta than CADI, used

**Table 1.** Chemical composition for the different alloys evaluated [weight %].

Alloy	C	Si	Mn	S	P	Cu	Ni	Cr	EC
C1	3.35	3.09	0.18	0.039	0.042	0.67	0.58	2.59	4.38
C2	3.40	3.00	0.13	0.015	0.039	0.65	0.56	2.04	4.40
C3	3.29	3.28	0.15	0.019	0.035	0.60	0.59	1.45	4.38
C4	3.18	3.38	0.13	0.016	0.037	0.63	0.61	0.84	4.31
C5	3.40	3.34	0.17	0.019	0.035	0.62	0.63	0	4.51



Fig. 1. New CADI prototype screw (left), and worn original steel screw (right).

as the reference material ( $\Delta V_R$ ), and the CADI samples ( $\Delta V_S$ ), as set forth in Eq. (1). Weight loss values were measured by means of a 1 mN precision scale and then converted into volume loss by means of the material's density measured on calibrated blocks made from all the alloys.

$$E = \frac{\Delta V_R}{\Delta V_S} \dots\dots\dots(1)$$

The meaning of the  $E$  value can be clearly illustrated by the following example:  $E=1.50$  indicates that the wear resistance of the material under evaluation is 50% higher than that of the reference material.

## 2.2. Screws for Animal Food Extruders Trials

In this case, four CADI prototype screws weighting  $\sim 45$  N were produced (Fig. 1). The melt used was eutectic and alloyed with 2.5% Cr (C1 in Table 1). The austempering temperature selected was  $T_a=280^\circ\text{C}$  in all cases. The chromium content and the austempering temperature used were selected so that the hardness obtained were as similar as possible to that of the original screws ( $\sim 560$  HBW<sub>2.5/187.5</sub>) made of martensitic cast alloyed steel, and used as reference material in the trials.<sup>17)</sup> The wear scar of a worn screw and the absence of impact loads in this application were also considered.

## 2.3. Wheel Loader Bucket Edges Trials

Another field trial of CADI machine parts was performed on wheel loader bucket edges (Fig. 2(a)) weighting about 100 N. Figure 2(b) illustrates the position of the edges in the bucket of a Caterpillar 950 F wheel loader. Two heats were alloyed with 1.0% Cr and 2.0% Cr (C4 and C2, respectively, in Table 1) and used to produce CADI edges, one with low carbide content and the other with a significantly higher amount of carbides.<sup>17)</sup> Another heat without Cr (C5 in Table 1) was employed to obtain the ADI edges used as a reference trial material. The austempering temperature selected was  $T_a=300^\circ\text{C}$  in all cases.

## 2.4. Wear Scar Analysis and Scratch Tests

The wear mechanism was studied by conducting scratch tests on samples derived from a CADI variant alloyed with 2.0% Cr (C2 in Table 1), austempered at  $T_a=320^\circ\text{C}$ , and with a carbide content of  $\sim 13\%$ . The samples were prepared by conventional metallographic polishing techniques.



Fig. 2. a) Wheel loader bucket edges; b) Edges position in a Caterpillar 950 F bucket.

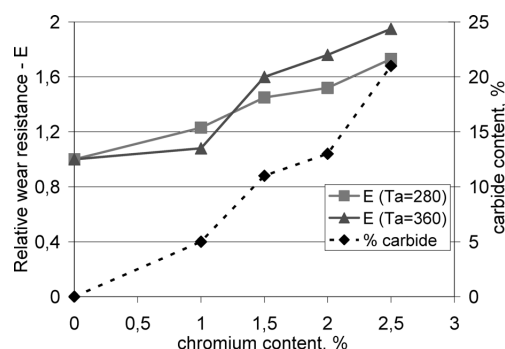


Fig. 3. Laboratory relative wear resistance (ASTM G 65) of some CADI variants austempered at two different  $T_a$ . ADI samples austempered at the same  $T_a$  than CADI were used as reference material ( $E=1$ ).

In order to clearly observe the carbides in the subsequent microscopic analysis of the scratches, the samples were etched with 10% ammonium persulfate in aqueous solution.

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.

## 3. Results and Discussion

### 3.1. Laboratory Abrasion Tests

Figure 3 presents the relative wear resistance ( $E$ ) values obtained in the laboratory for all CADI samples (obtained from alloys C1, C2, C3 and C4, Table 1) at the two austempering temperatures evaluated,  $280^\circ\text{C}$  and  $360^\circ\text{C}$ . The reported values are the average of four determinations, with a maximum  $\sigma_{n-1}=0.06$ . The carbide content corresponding to each CADI variant is also shown for reference in Fig. 3. As seen, abrasion resistance increases with chromium con-



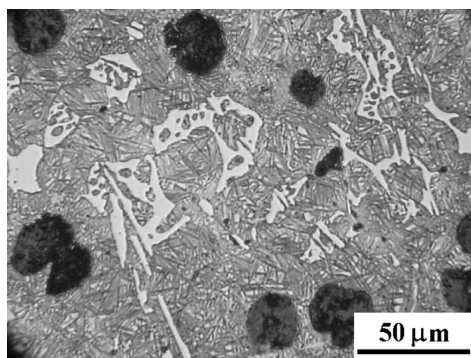


Fig. 4. Microstructure at the cross section of a CADI extruder screw. The austempering temperature was 280°C.

tent, and so with carbide content and hardness. It can also be noticed that the reinforcing effect of carbides is greater in the softer matrix ( $T_a=360^\circ\text{C}$ ).<sup>17)</sup>

### 3.2. CADI Animal Food Extruder Screws Trials

The microstructure typically observed in the cross section of CADI prototype screws yielded graphite nodules (dark phase) with good nodularity and a carbide content of ~21% (white phase), immersed in an ausferrite matrix (Fig. 4). Said carbide content was in agreement with the results reported in a previous work by the authors for melts with similar %Cr.<sup>17)</sup> The matrix resulted completely ausferritic and hardness was ~510 HBW<sub>2.5/187.5</sub>.

In line with the results obtained from the field trials, the abrasion resistance of CADI screws was higher than that of the original martensitic steel screws. In this case, the wear resistance was evaluated in terms of the food processed mass per millimeter lost in the screw diameter. Average values of 280 t/mm for the CADI screws and of 228 t/mm for the steel screws were obtained.

### 3.3. CADI Wheel Loader Bucket Edges Trials

Figures 5(a) and 5(b) show the microstructure observed in the cross section of the CADI edges with 1.0% Cr and 2.0% Cr, respectively. For the variant containing 1.0% Cr, the carbide content was ~5% and hardness amounted to 460 HBW<sub>2.5/187.5</sub>, while for the 2.0% Cr variant, the carbide content was ~13% and hardness was of 470 HBW<sub>2.5/187.5</sub>. These carbide contents are consistent with the previous results accounted for by the authors.<sup>17)</sup> The matrix resulted completely ausferritic after the heat treatment in both cases, denoting the adequate austemperability of the alloys for the part size and the austempering media employed.

Under the wear conditions laid down by this application, both CADI variants showed lower wear resistance than ADI did, as depicted in Fig. 6. Besides, it should be pointed out that the lowest abrasion resistance was obtained for the variant with the highest chromium and carbide content, and hence with the highest hardness.

### 3.4. Wear Scar Analysis

As discussed in the Introduction section, the results described above demonstrate, once again, that ductile iron, CADI in this particular case, may respond either positively or negatively to abrasion, depending on the tribosystem.

Figures 7(a), 7(b), and 7(c) illustrate the wear scars cor-

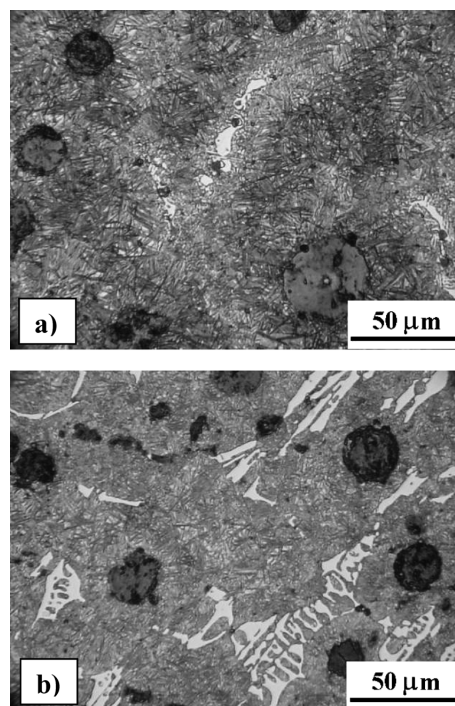


Fig. 5. Microstructure at the cross section of CADI wheel loader bucket edges containing a) 1.0% Cr, and b) 2.0% Cr. The austempering temperature was 300°C.

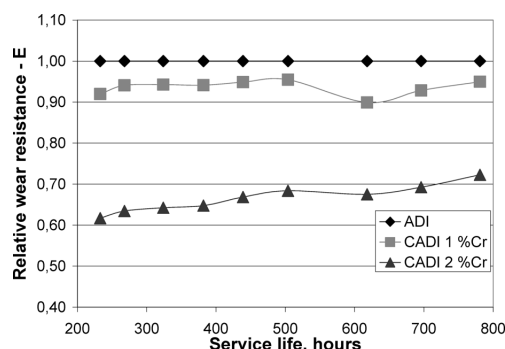


Fig. 6. Relative wear resistance of CADI bucket edges vs. service time of the wheel loader. ADI segment used as reference material ( $E=1$ ).

responding to a laboratory wear test sample, an extruder screw and a bucket edge, respectively. In Fig. 7(a), the surface appears smooth with small and parallel scratches, having low width (~30 μm) and depth. In Fig. 7(b) the surface also appears smooth, yet, in this case, the small scratches cannot be appreciated due to the magnification used. Conversely, in Fig. 7(c), the wear scar appears rougher, with scratches up to ~250 μm width (this is about one order of magnitude wider than those in Fig. 7(a)), thereby signifying greater plastic deformation, with material displaced to the edges of the groove.

The extension of plastic deformation below the surface is depicted in Figs. 8(a) and 8(b) for the extrusion screws and bucket edges, respectively, where sections perpendicular to the worn surfaces (arrowed) are shown. As it can be observed, the microstructure was plastically deformed following the wear direction up to a depth of ~5 μm for the screws, while, for the edges, the more severe abrasion could affect the material up to ~100 μm below the surface.

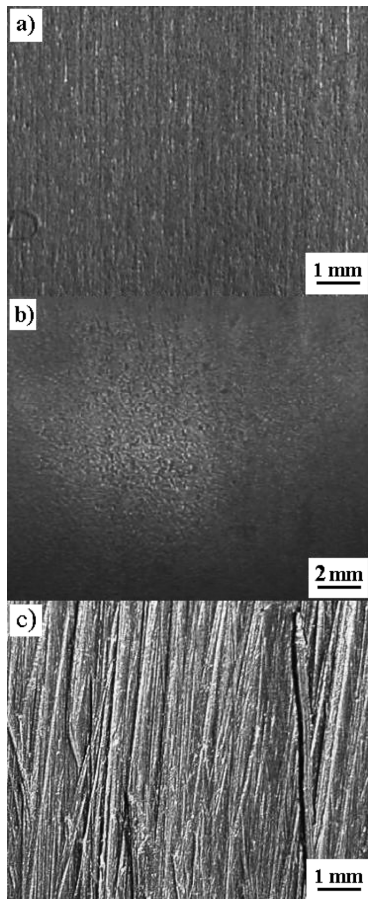


Fig. 7. Macroscopic view of the wear scars, a) laboratory samples, b) extruder screws, and c) wheel loader bucket edges.

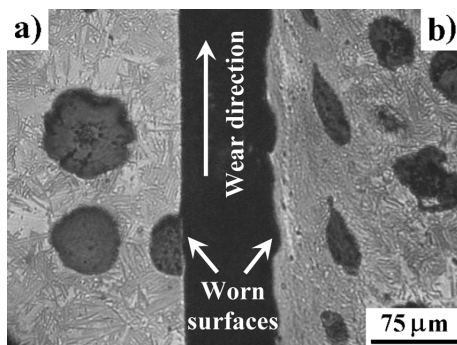


Fig. 8. Microstructure under the wear scars, a) extruder screws (low abrasion severity), and b) wheel loader bucket edges (high abrasion severity).

The analysis of Figs. 7 and 8 show that the abrasiveness of the extruder screw as well as the laboratory tribosystems can be considered of low stress type, whereas that of the bucket edges can be considered of high stress type.

#### 3.4.1. Scratch Tests

Scratch tests were conducted in order to study the abrasive wear micromechanisms taking place in the different tribosystems under study. **Figure 9** shows SEM micrographs of CADI microstructures and the different scratches obtained with a 1 N load. As observed, the abrasive particle (in this case, the Vickers indenter) produces a nearly 20 μm wide scratch on the ausferritic matrix with a hardness of

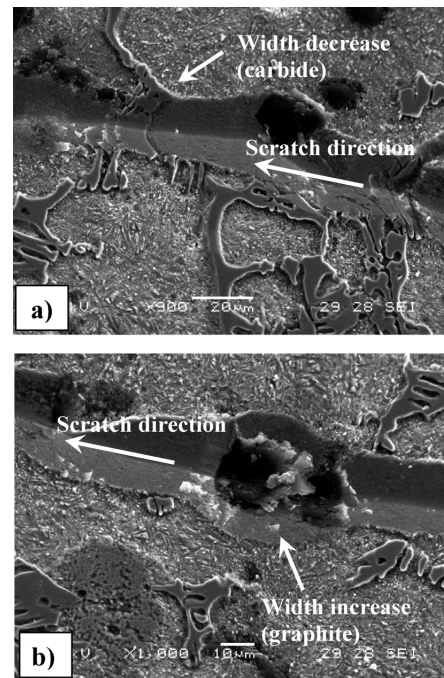


Fig. 9. SEM micrographs of CADI microstructures and different scratches made with a 1 N load.

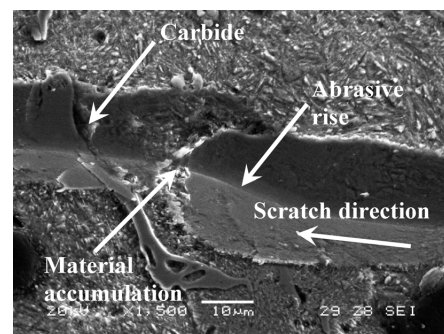


Fig. 10. SEM micrograph of CADI microstructure and a scratch made with a 1 N load.

~440 HV<sub>200</sub>. The reinforcing effect of the carbides (with a hardness of ~1 100 HV<sub>200</sub>) can also be noticed, as they are capable of sustaining the load with a lower tip penetration, denoting a lower scratch width, Fig. 9(a). Nevertheless, it should be considered that carbides are also abraded by the same micromechanisms responsible for the wear of the rest of the matrix, *i.e.*, microploughing and microcutting.<sup>12)</sup> Besides, when the indenter travels over a softer phase like graphite, the scratch width increases notoriously, Fig. 9(b).

**Figure 10** illustrates the decrease in the penetration depth when the abrasive particle reaches a carbide in its sliding path. The material accumulation in front of the carbide can also be observed. Moreover, as shown in **Fig. 11**, the carbides are frequently fractured due to their very limited ductility, if compared to that of the ausferrite.

As for the scratches obtained with a 1 N load, their nearly 20 μm width 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 (Figs. 9 and 10).

**Figures 12(a)** and **12(b)** illustrate the scratches obtained by using a 10 N load, in this case ~75 μm wide, which is



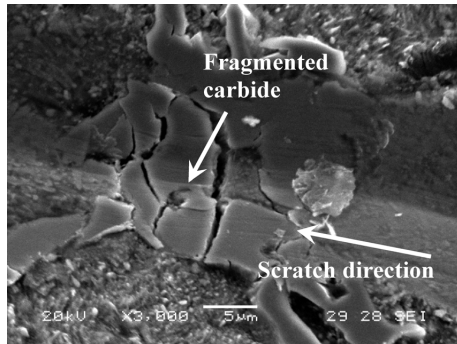


Fig. 11. SEM micrograph showing a detail of carbide fracture during scratching. The load used was 1 N.

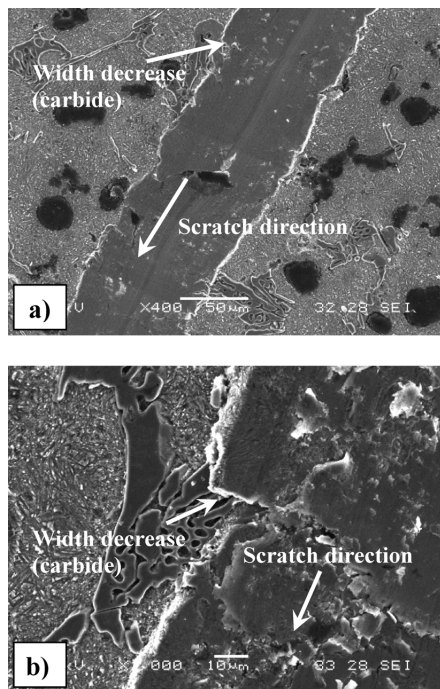


Fig. 12. SEM micrographs of CADI microstructures and different scratches made with a 10 N load.

comparable to those present in the worn surface of the bucket edges, though larger than the average carbide size.

### 3.5. Discussion

Based on the results above, a possible explanation for the good CADI performance under low stress abrasion, like that of the extruder screws or the laboratory tests, could be groove size, which is similar to that obtained when scratching with a 1 N load. By using this load, the groove size is smaller than that of carbides, which are therefore able to play a reinforcing role.<sup>12)</sup> 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.

Despite the foregoing, as shown in Fig. 11, the carbides are worn by microfracture, resulting in fragments weakly bonded to the matrix and ready to be pulled out in the following abrasive passage. Then, microfracture can be assumed to be the main carbide wear mechanism.

On the other hand, the unsatisfactory behavior reflected by CADI wheel loader bucket edges, where abrasion is con-

sidered to be of high stress type, can be justified by the large scratch size (up to  $\sim 250 \mu\text{m}$  width) compared to that of carbides. The scratch tests, together with a previous work by Zum Gahr,<sup>12)</sup> showed that, being the chip size 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.

Furthermore, as carbide content increments with %Cr increase, abrasion resistance decreases. At this point, it is worth considering that chip formation is a plastic strain process that demands a certain amount of energy. When carbides are present, the material's ductility decreases drastically and then much less energy is required to create a chip and to remove material. The chip becomes brittle and breaks easily, which lowers energy consumption for the abrasion process to take place, and consequently abrasion resistance decreases. Such behavior is supposed to change for an even greater amount of carbides, there where the distance between the reinforcing particles do not allow abrasive particles to deeply penetrate the surface.

### 4. Conclusions

Based on the results obtained in the laboratory and field 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.

When abrasion is of low stress type (like that of the ASTM G 65 laboratory wear tests and extruder screws trials), wear resistance is tied to the abrasive particle penetration depth decrease promoted by carbides, which satisfactorily play the reinforcing role. Then, abrasion resistance increases with carbide content, and hence with hardness.

When abrasion is of high stress type (like that of the wheel loader bucket edges trials), the worst wear resistance yielded by CADI can be justified by the scratch size being greater than that of carbides, thus becoming less effective as reinforcing particles. Additionally, the presence of carbides renders the chip brittle, thereby reducing the energy consumption in the abrasion process. Then, under this condition, the increase in carbide content worsens CADI abrasion resistance.

It is worth noticing at this point that the good technical-economical result reached with CADI extruder screws is reflected in their actual use by the animal food factory.

There are many real tribosystems whose wear scar, and hence stress level, mirrors that of extruder screws, opening new horizons for CADI parts potential application fields.

### 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 and R. Dommarco: *ISIJ Int.*, **49** (2009), No. 1, 132.
- 5) R. Dommarco, H. Dall'O and H. Ortiz: *Anales Jornadas Metalúrgicas, Sociedad Argentina de Metales (SAM), Buenos Aires, Argentina, (1991), 99.*
- 6) H. Dall'O, H. Ortiz and R. Dommarco: *Anales TRIBOS'94, Jornadas Tribológicas de la Rep. Argentina, Centro Argentino de Tribología, Buenos Aires, Argentina, (1994).*

- 7) J. García, J. Sikora and H. Dall'O: Anales TRIBOS'94, Jornadas Tribológicas de la Rep. Argentina, Centro Argentino de Tribología, Buenos Aires, Argentina, (1994).
- 8) J. Sikora, J. Capurro, J. García and H. Dall'O: Anales Jornadas Metalúrgicas, Sociedad Argentina de Metales (SAM), Bahía Blanca, Argentina, (1994), 137.
- 9) Ductile Iron Data for Design Engineers, QIT-Fer et Titane Inc., Montreal, Quebec, Canada, (1990), 4.
- 10) J. M. Vélez and A. P. Tschiptschin: Anales 50º Congresso Anual da Asociacion Brasileira de Metales (ABM), Aguas de Sao Pedro, Sao Paulo, Brazil, (1995), Vol. 2, 1.
- 11) W. S. Zhou, D. Q. Zhou and S. K. Meng: *Cast Met.*, **6** (1993), No. 2, 69.
- 12) K. H. Zum Gahr: *Tribol. Int.*, **31** (1998), No. 10, 587.
- 13) B. A. Ceccarelli, R. C. Dommarco, R. A. Martínez and M. R. Martínez Gamba: *Wear*, **256** (2004), 49.
- 14) J. V. Giacchi, R. A. Martínez, M. R. Martínez Gamba and R. C. Dommarco: *Wear*, **262** (2007), 282.
- 15) J. R. Keough and K. L. Hayrynen: *Ductile Iron News*, **3** (2000).
- 16) K. L. Hayrynen and K. R. Brandenburg: *Am. Found. Soc.*, **111** (2003), 845.
- 17) S. Laino, J. Sikora and R. Dommarco: *Wear*, **265** (2008), 1.
- 18) S. Laino, J. Sikora and R. Dommarco: *ISIJ Int.*, **49** (2009), No. 8, 1239.