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Wear Characteristics of ADIs; A Comprehensive Review on Mechanisms and Effective Parameters

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ABSTRACT

Among industrial alloys, cast irons have the most variable characteristics with the lowest price; of these groups, ADIs have been attracted in industry because of their favorite properties to be replaced by forged steels. One of these properties is their desirable wear behavior. The predominant wear mechanism in ADIs is delamination of spherical graphites to oval ones, crack propagation from stress concentration centers and producing larger cavities by pulling off graphites due to plastic deformation. There are different methods for improvement wear resistance in these materials such as; reducing austempering temperature, increasing hardness of surfaces in contact, increasing the fineness of ausferritic matrix, work hardening of ferrite phase, increasing the amount of high-carbon retained austenite at ambient temperature. Another way for reaching this purpose is the production of carbidic austempered ductile irons (CADI) with implementation of carbidizing alloying elements and or by chills.

KEYWORD: Austempered Ductile Iron (ADI), Wear properties, Relative Wear Resistance (RWR), Delamination Mechanism.

1. INTRODUCTION

The need of making structures with much more ductility and hardness in cast irons led to extensive researches in changing microstructure of these materials [1-3]. ADIs are one of the most significant results of these investigations. According to Isothermal Transformation (IT) diagrams, austempering is an ability and capacity of cast irons in passing through pearlite nose while cooling from austenitizing temperature (850°C - 950°C) to austempering temperature (230°C - 450°C) without intersection with the nose of diagram, because pearlite formation as a result of an incorrect austempering treatment damages the ADI's mechanical properties [2,4]. Austempering in steels leads to upper or lower bainite microstructures which include needle ferrite together with tiny carbide participates; however, in ductile irons, it includes two stages. Therefore, it is preferred to call these irons as Austempered ductile iron rather than bainitic ductile iron to emphasis on the difference in microstructure [4,5]:

First Stage of Transformation: $\gamma \rightarrow \alpha + \gamma_H$
Second Stage of Transformation: $\gamma_H \rightarrow \alpha + \text{carbide}$

Austempering transformation is started with nucleation and growth of ferrite phase in austenitic matrix. At the end of first stage of transformation, the structure includes ferrite and austenite enriched in carbon which its continuous nature is the reason of high toughness and ductility of ADIs, additionally, distribution of ferrite plates leads to high strength. In the second stage, austenite enriched in carbon (γ_H) is decomposed into two more stable phases; ferrite and carbide [5,6]. Successful growth of ADIs is because of the following advantages:

- Inexpensive raw materials and casting ductile iron with ease in comparison with steels [1].
- Higher Strength to Weight ration in comparison with steels [1,2,6].
- Higher damping capacity in comparison with steels [1,2].
- Higher fatigue strength of ADI parts compared with different types of cast irons (gray, malleable and ductile) and its competitive strength some other engineering steels [7,8].
- Ability to access to a wide range of characteristics with appropriate selection of heat treatment parameters [6,7].
- ADI parts' higher wear resistance due to work-hardening phenomenon of the retained high carbon austenite and its transformation to martensite because of high stress atmosphere on the surface [2,9].

Since one of the most significant applications of ADI parts are in wear environments, it seems necessary to investigate wear behaviour of these cast irons.

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2. WEAR

2.1. Wear Processes

Tribology is defined as the science and technology related to behaviour of counterface surfaces with relative movement of them. This scientific branch includes subjects as such as friction, wear and lubrication. Wear can be defined as "the process of materials damage or removal from solid surfaces being in contact with each other" [10]. Key factors influencing on wear phenomenon are as following:

- Metallurgical variables such as hardness, toughness, microstructure and chemical composition.
- Wear condition such as materials in contact and friction coefficient among them, type and method of loading.
- Speed of movement of surfaces on each other, temperature, time, surface toughness and type of lubricant material [11].

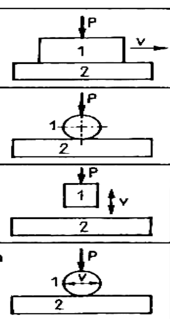
Some materials with suitable resistance against one type of wear process may be extremely sensitive against other kind of wear; therefore, different types of wear should be classified to survey wear damage in various situations [12]. The most authoritative classification was made on the base of dominant mechanism influencing on it.

2.2. Wear Mechanisms

Wear mechanisms focus on factors such as plastic deformation, ductile and brittle fracture, shear, fatigue, adhesion and chemical effects [10]. Generally, application and condition governing on the surface can determine the dominant mechanism in wear of materials. For parts with mechanical applications, different kinds of adhesion, oxidative and fatigue wear are more important. Fig. 1 indicates the relationship between these wear processes with type of surface contact of two pieces.

2.2.1. Abrasive Wear

This method of wear happens when asperities of a hard surface or hard particles between two surfaces slide on a softer surface and damage it. Abrasive wear is divided into two kinds of two-body and three-body ones according to abrasive particles between the counterfaces. In two-body type, the abrasive particles are located on the harder surface and make abrasion of the surface by moving on a softer surface, while in three-body type, the particles can slide or rotate easily among the surfaces and make one or two sides in contact abraded [10].



Type of relative motion of mating elements *1* and *2*	Dominant mechanisms of wear: abrasive	by oxidation	adhesive	fatigue (pitting, spalling)
Sliding	●	◐	●	●
Rolling	◐	●	◐	●
Dynamic	●	●	○	○
Oscillation	Wear by fretting = combined effect of all types of friction			

● – Occurs with strong intensity
◐ – Occurs with mild intensity
○ – Practically does not occur

Fig. 1. The relationship between kind of surface contact and wear mechanism [13].

2.2.2. Adhesive Wear

Adhesive wear happens normally in low speeds and high pressure and among those surfaces which are sliding on each other. The mechanism of adhesive wear works on the basis of particles separation due to adhesive connection or what is called "Cold Weld". In this mechanism, particles are separated from the surface together with plastic deformation [13]. An important point should be considered in study of adhesive wear is formation of a transient layer. Separated particles due to abrasive wear are moved among the surface in contact. These particles can make a transient layer on the counterfaces prior to be released as debris [10].

Adhesive wear has different grades of damage called Galling, Scuffing and Seizing. When adhesion and fracture of particles are in big scales, galling process will happen which results in much more damages on the metallic surface. Medium state of adhesive wear, named scuffing, has less damaging effect than galling, while results still indicate the removal of a considerable amount of the metallic material from the counterfaces. The least amount of adhesive wear is seizing with the least damaging effects [11].

2.2.3. Oxidative Wear

Oxidative wear is dry metals sliding in air or exposure to oxygen. Temperature rise because of metallic pairs sliding makes an oxide layer with few microns thickness on counterfaces. This oxidative layer is destroyed a few minutes after being formed due to contact sever effects. After a while the layer will be made again. This repetitive cycle forms the oxidative wear mechanism [14]. Oxidative mechanism depends dramatically on sliding speed and temperature.

2.2.4. Fatigue Wear

Applying alternative stress on materials surface layers can result in formation of fatigue stress. Fatigue wear mechanism can be surveyed with base of stress performance in the area under the contact surface. When two surfaces move on each other, stress distribution under the contact surface is in a way that maximum shear stress will be happened in a short depth from the surface. Stress increase under the surface makes microcracks in this area. These cracks are nucleated from maximum shear stress points and then propagated towards the surface [12].

2.2.5. Delamination Wear

Delamination wear can be compared with onion pealing. According to this theory, plastic deformation, shear, crack nucleation and its propagation in a shallow depth of surface leads to Delamination separation. Increasing slide distance, dislocations are collected in a short distance from surface which results in microporosity formation. Through time, porosities are combined together and a crack is formed along with the surface. When the crack gets a critical length (depending on material's properties), the material between the crack and the surface is separated as a delaminated particle [14].

3. WEAR IN ADIS

Several researches confirm wear resistance of ADIs in various environments. Reported features include rolling wear, impact wear and sliding wear resistance without lubricants [15,16,17]. Fordyce et al. [16] showed that ADIs have very high dry sliding wear resistance which equals with the resistance of very hard steels, specially in higher sliding speed. Liu Ping et al. [17] showed that for ADI and austempered steel with a relatively similar matrix, wear resistance of austempered steel is more than ADI, because graphite in cast iron is the weakness point in wear resistance; and empty graphite holes are suitable places for microcracks nucleation [18]. However, some researchers believe that in a uniform hardness (not in a uniform microstructure) wear resistance of ADIs is much more than steels [19]. One of the reasons is graphite's lubrication ability in cast irons. Graphite in cast irons works as a lubricant and declines friction which results in less friction coefficient of ADI than austempered steels [17]. Prasanna [20] and Voight [21] believe that when the produced ausferritic matrix becomes finer, it will have a considerable increase in Relative Wear Resistance (RWR). Hasseb et al. [22] showed that TRIP[1] mechanism reacts as the unique wear behaviour of ADIs. Owhadi et al. [23] and Schissler [24] found out that a fraction of retained martensite lower than 0.1% is beneficial in case of wear properties improvement. They, also, believe that work-hardening of ferrite phase is another reason of wear resistance improvement in these irons. In a similar study, Nili et al. [25] showed that the wear resistance of an ADI containing 0.75 wt.% Mn increases proportionally with increasing the retained austenite carbon content and decreasing the Untransformed Austenite Volume (UAV). Totally, wear resistance in ADIs is due to the following reasons:

1. Work-hardening of retained austenite in surface layers during wear process [17].
2. Retained austenite transformation to martensite due to plastic deformation in surface layers [13]. To do this transformation, low-carbon austenites act better than high-carbon ones because they have lower mechanical stability. Therefore, austenites in UAV regions or in other words blocky austenites, which have less carbon than other ones, are converted into martensite with ease, however, high-carbon austenite need much more stress to be transformed [19].
3. Presence of casting carbides with high levels of hardness [26].
4. Increasing the fineness of bainitic structure by lowering austempering temperature, alloying elements such as V and B, and increasing solidification rate by means of metallic moulds or chills [19].
5. Precipitation of ε-carbide during the first stage of austempering process which occurs in low temperatures [26].

[1] Transformation Induced Plasticity

3.1. Effects of Different Factors on ADI Wear Resistance

3.1.1. Austempering Temperature

Decline of austempering temperature leads to increase RWR, this is because of lower bainite formation with higher hardness and mechanical strength than the upper bainite, increase of fineness of ausferrite matrix, and decrease of UAV [3,4,15,19,27,28].

Microstructure of ADI including Cu-Ni-Mo for two austempering temperature of 315 and 370°C is indicated in Fig. 2 where increase of matrix structure fineness along with austempering temperature decline is obviously clear. Volume fraction of retained austenite and RWR for several austempering conditions are shown in Fig. 3.

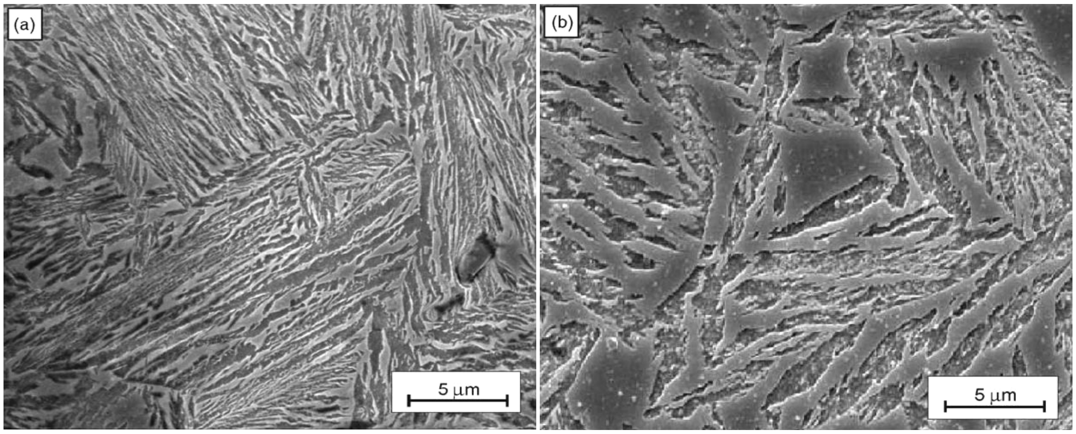


Fig. 2. SEM microstructure of ADI austempered at: a) 315°C and 240 min; b) 370°C and 240 min [29].

According to Fig. 3, RWR for samples austempered at 315°C is higher than the same amount for samples austempered at 370°C which is due to finer microstructure in low austempering temperature. On the other hand, because of decline in austempering temperature, volume fraction of retained austenite will be decreased due to lower carbon diffusion. In addition, TEM observations unveil hexagonal ε-carbide precipitations in interface of α/γ and inside of ferrite needles in 315°C. At austempering time of 370°C, orthorhombic η-carbide is seen in ferritic matrix and α/γ interface [30,31].

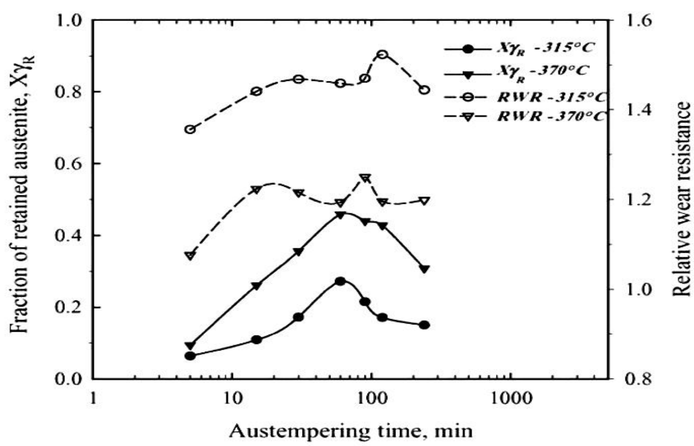


Fig. 3. Volume fraction of retained austenite and relative wear resistance for different conditions of austempering heat treatment [29].

3.1.2. Austempering Time

Several researches' outcomes indicate that in short austempering times, ADI wear resistance is low at first and then increases, and after a maximum it declines once more; because in short austempering times, UAV is higher in bainitic structure. This UAV amount in isothermal austempering treatment cannot find time for enriching with carbon, it dose not have thermal stability and is seen as martensitic or martensitic-austenitic at environment temperature [29,32,33]. On the other hand, the carbon content of retained austenite (C_γ) is low, and apart from the retained martensite in the microstructure, it is possible to change the low-carbon retained austenite to martensite in sample's surface layers during wear test. The stress application on the sample surface in wear atmosphere provides instability condition for the retained austenite with less carbon. Therefore, low RWR in short austempering times is due to factors such as considerable amount of martensite in UAV region, higher amount of UAV and mechanical instability of the retained austenite. By increasing austempering time, UAV is declined, and is revealed in austenitic-martensitic and austenitic forms [22].

As it is seen in Fig. 4, austempering time rise leads to increase in retained austenite amount and its carbon. Increase in the retained austenite provides the required material for hardworking and its transformation to martensite, but increase in carbon which results in austenite stability, makes hardworking of austenite more probable instead of transformation of austenite to martensite [24,32].

Through passing the austempering time and due to second stage of austempering which means decline of retained austenite, wear resistance decrease. This is because of reduction in the amount of the material required for work-hardening and transformation to martensite in surface layers [32].

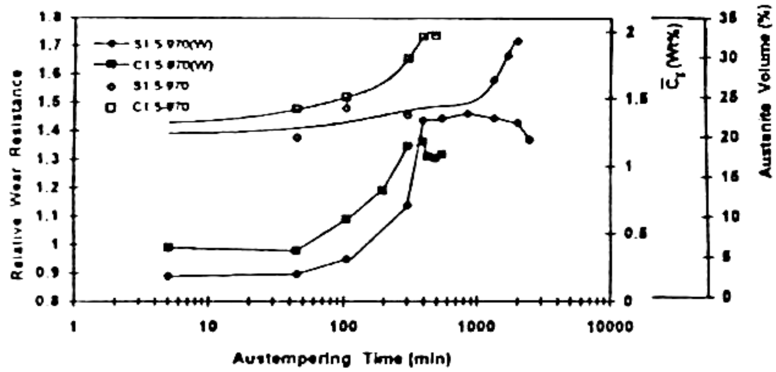


Fig. 4. Variations of RWR and the retained austenite and its carbon content with austempering time in 1.5%Mn ADI austenitized at 970°C [32].

3.1.3. Austenitizing Temperature

To consider the effects of austenitizing temperature on the wear resistance of ADIs, it is essential to focus on both these factors; carbon content of austenite and the amount of UAV. The optimized austenitization temperature can be selected, thereafter. Increase in austenitizing temperature will increase the carbon solubility in austenite; therefore, carbon content of austenite goes up [5, 34]. On the other hand, the amount of UAV will increase if the austenitization temperature rises up [32]. Increment in UAV increases the fraction of martensite at ambient temperature; however, increase in carbon content of austenite makes it more stable. At same austempering temperature, the final microstructure will be coarsened by increasing the austenitizing temperature; is such a manner that needle-like bainite changes into coarse feather-like ones [35]. Putting all above-mentioned points into consideration, it is the most dominant opinion between researchers that increasing the austenitization temperature will improve relative wear resistance of these materials, totally [27,28,36-38]

3.1.4. Austenitizing Time

Soaking time at austenitizing temperature must be selected as whole matrix transforms to FCC austenite, firstly and carbon atoms distribute homogeneously all over the matrix, secondly [39]. Moore et al. [40] and Rouns et al. [41] indicated that austenitizing times lower than 2 hours result in uncompleted austenitic transformation and considerable amount of UAV as well as heterogeneous distribution of carbon in austenite matrix; therefore, RWR increases with increment of austenitizing temperature. Not to mention the fact that if austenitization soaking time exceeds an optimized time, wear resistance will decrease due to grain growth and resulted coarse structure [27,40,41].

3.1.5. Hardness of Counterfaces

When hardness of surfaces in contact increase, surface damage and as a result sample weight loss will be decreased and RWR will be increased, subsequently. Fig. 5 shows the comparison of ADI wear resistance with that of steel according to their hardness. This wear resistance is measured by pin-on-disc method.

Increasing hardness leads to rise of ADI and steel's wear resistance, while as it is seen in Fig. 5, increase of hardness has more effect on wear resistance of steel than ADI, because in ADI's wear, transformation agent of the retained austenite to martensite plays more controlling role than hardness [15,19,42,43].

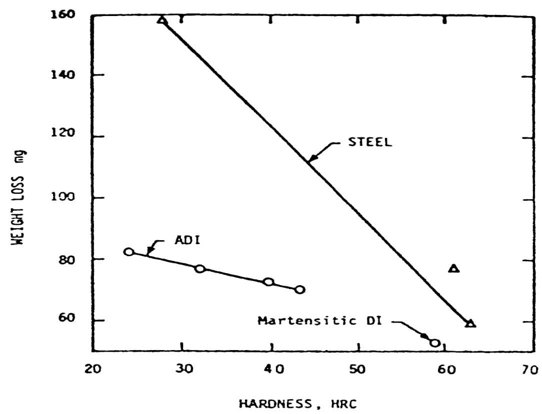


Fig. 5. The relationship between weight loss with hardness in pin-on-disc test [19].

3.1.6. Solidification Rate and Nodule Count

To investigate the effects of solidification rate and graphite nodule count, two samples with 192. N.C./mm^2 (High N.C.) and 65 N.C./mm^2 (Low N.C.) were experimented. Also, sliding wear test was conducted in dry condition by pin-on-ring method and applying 300N load. Weight loss of ADI samples is presented in Fig. 6 as a function of sliding time for Low N.C. and High N.C. [25].

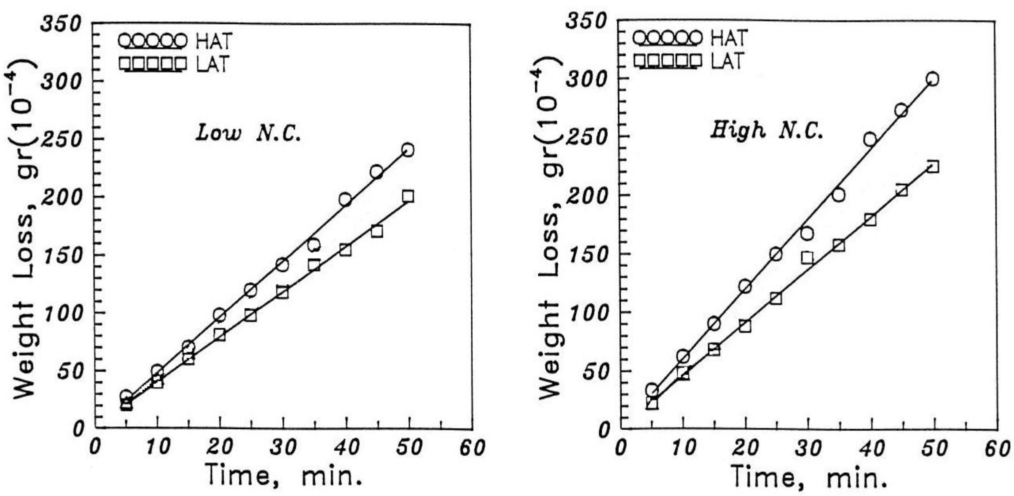


Fig. 6. Weight loss v.s. sliding time under applied 300N load for the samples with high and low nodule count, austempered in 375°C (HAT) and 315°C (LAT) [25].

According to Fig. 6, it is obvious that samples with less solidification rate (less graphites nodules number) have more wear resistance, because delaminated regions around graphites are one of the sources of making wear debris. Therefore, graphite nodule count decline through increasing solidification time or in the other word decreasing solidification rate will increase the regions which making wear layers. These wear layers lead to wear debris [25,32].

For less applying loads in wear condition, as the matrix microstructure controls the wear resistance, rise of graphite nodule count declines matrix effective section area and consequently wear resistance decreases. Therefore, samples with low solidification rate indicate better wear resistance. On the other hand, rise of graphite nodule count increases thermal conductivity; and as temperature increase results in decline of yield strength, plastic deformation and wear increase strongly, so graphite presence stops temperature elevation and its detrimental effects. A combination of these two phenomena controls wear rate [11].

3.1.7. Stress Level in Wear Atmosphere

The austenite in ausferrite is stable thermodynamically and not mechanically; where a high enough normal force applied on an austempered structure, transformation of austenite to martensite occurs. This happening produces a hard tough layer of were resistant martensite supported by ausferritic tough structure. The ability of martensite formation in such circumstances is one of the main reasons of ADIs' desirable high wear resistance [23,44].

Typically, wear tests are divided into two groups in terms of level of applied stress: atmospheres with enough high stress which makes the surface hard working and the transformation of the retained austenite inside ausferrite to martensite possible, and atmospheres with less stress levels which not enough to form martensite. Dry Sand / Rubber Wheel (DSRW) with a low stress atmosphere wear test results is indicated in Fig. 7 and for pin-on-disk test with a high stress media is shown in Fig. 8.

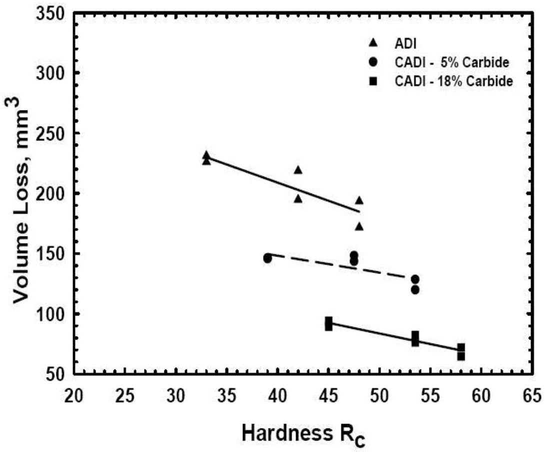


Fig. 7. DSRW test results (low stress atmosphere) [44]

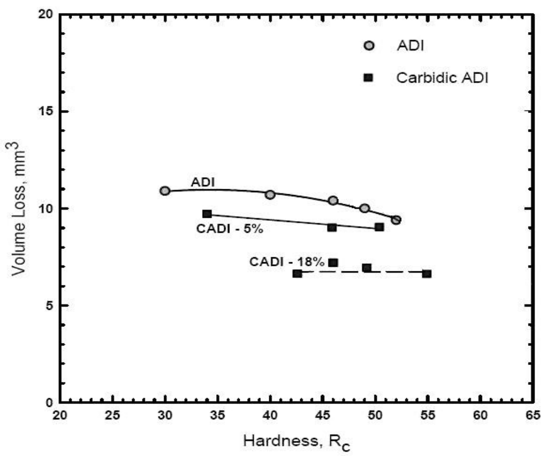


Fig. 8. Pin-on-Disc test results (high stress atmosphere) [26].

According to these two figures, it is clear that in DSRW test curves related to ADI have much more slope than pin-on-disc test. It is due to less normal forces, which in this state, are not enough to make transformation of austenite to martensite possible, while in pin-on-disc tests, curves related to ADI are a little bit, flat smooth which shows that weight loss is not sensitive to hardness. This is because of austenite to martensite useful transformation in the samples' surface [19,43,45].

3.1.8. Graphite Morphology

Since dominant wear mechanism in ADIs is crack nucleation from graphite nodules and material's layers separation by delamination, graphites morphology and nodularity percent of graphites are of importance. To evaluate the effects of graphites' morphology, three types of cast irons with flake graphite (FC), vermicular compacted graphite (CV) and spheroidal graphite (FCD) were investigated in wear test [46]. The outcomes indicated that decrease in nodularity of graphites from FCD through CV and FC, wear resistance of samples declines, dramatically. In FC and CV samples, due to lower average distance between graphites and less metallic matrix continuity, cracks nucleation and interconnection to each other takes place with ease in comparison with FCD samples; therefore, considerable amount of wear debris will be produced. Furthermore, in FCD samples, graphites have lower stress concentration which results in higher wear resistance than FC and CV [3,46,47]

3.1.9. Presence and Amount of Carbide Phase in the Structure

Carbidic Austempered Ductile Irons (CADIs) are members of ADIs including carbide which support wear resistance and toughness, both together. As desirable wear properties with high level of surface hardness while keeping toughness can increase parts' life, tendency to provide carbide in ADIs can meet this need.

The following methods are used to produce carbide in the matrix [30,36];

1. By means of strong carbides in the melt (composite carbides).
2. By using of carbide-making elements.
3. Applying chills for making carbide in the surface of castings.

In CADIs, final microstructure includes a considerable volume fraction of carbides in ausferrite matrix. To produce carbides, one can use carbide-producing elements such as Cr, Mo and Ti. The carbides were produced in this way an unsolvable ones and their amount cannot be changed by next austempering treatment [44]. In one of the researches in this field, Hayrynen et al [26] applied Mo and Cr alloying elements in iron melt. These elements were selected as their carbides are very stable and try to keep their volume fraction even after austenitization as the volume they had in as-cast samples. The produced microstructure is shown in Fig. 9.

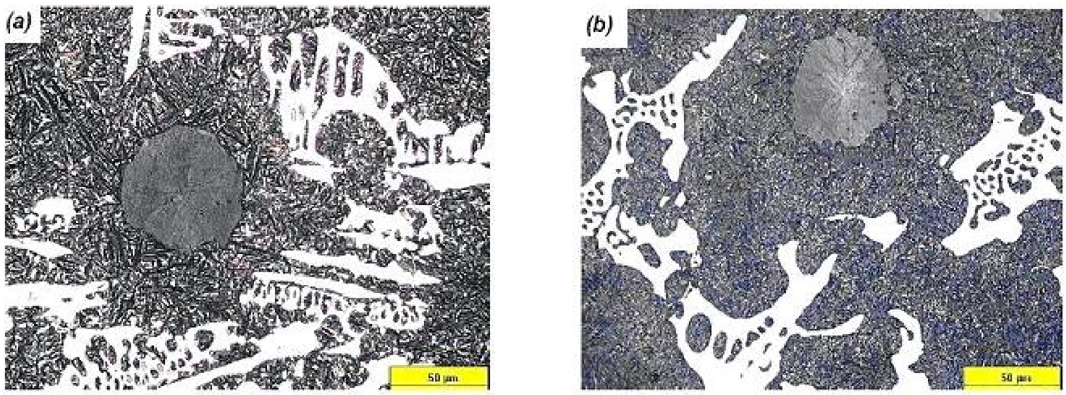


Fig. 9. CADIs microstructures austempered at a) 370°C and b) 260°C [26].

According to DSRW and pin-on-disc tests results in Figs 7 and 8 on both kinds of samples with low and high carbide in comparison with normal ADI, it is clearly seen that CADI has more wear resistance than ADI and carbide amount rise leads to improvement of wear resistance. This is due to carbide particles in ausferrite matrix which increase the hardness of matrix, having appropriate level of toughness, yet [26].

To produce CADI, chill conducting can be utilized. In this case, wear properties of these irons will have a direct relationship with solidification rate at the chilled parts. Rise of chilling speed or thickness of chills, will increase wear resistance and hardness [30].

Presence of Mo in Austempered Chilled Ductile Irons (ACDIs) produces eutectic carbides and eliminates interdendritic precipitations. This issue has considerable effects on wear resistance, UTS and toughness of parts especially in high austempering temperatures. Mo is a very effective element in precipitating of stable carbides in high temperatures, but Mo amounts more than 0.1 Wt% makes the structure heterogeneous [11,30]. According to the results of a recent investigations [30], wear resistance will be increased considerably with Ni amount rise at constant amount of Mo and generally by increasing Mo-Ni content of samples.

3.2. Wear Mechanisms in ADIs

The most common type of wear in industries, in which ADI is used, is sliding type where dry counterfaces slide on each other without any wearing material. This process initially commence with adhesive wear mechanism in which asperities of the surfaces are locked with each other and eradicate particles from the surfaces. The produced practices change the wear mechanism from adhesive to abrasive one [11,48].

Wear mechanism in ductile irons is of adhesive type of and plastic deformation, however, in ADIs plastic deformation is less and the surfaces include scotches, slight surface tractions and voids from graphite ruins which are deepened through time. In these conditions, tiny holes are produced by delimitation mechanism, while big holes are produced due to ruining graphite nodules [3,15]. While in steels, crack nucleation factor controls the wear rate and delimitation theory explains it, in ADIs, crack nucleation in graphites presence take place with ease than what is seen in steels. Graphites near the surface deformed easily and turned into ellipse ones, so they can act as a crack beneath the surface. Because crack nucleation happened easily, the crack propagation controls the wear in ADIs [15,29]. On the other hand, an oxidative layer is produced when one layer is worn on the other one. This oxidative layer is made up of FeO and Fe_2O_3. These layers are broken into wear debris because of plastic deformation and collision of surfaces' roughness if wear process be continued. As graphite has very low strength and has no elastic resistance against stress and contact of wear debris to the surface, empty points produced by graphites pulling out perform as the voids which crack nucleation toward to the surface originate from [16].

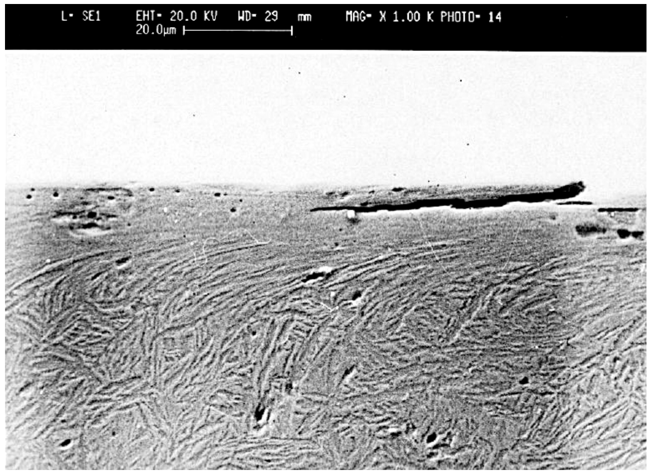


Fig. 10. SEM micrograph of worn surface of ADI sample with applying on. Porosity in the delaminated layer. Result the delaminated mechanism [25].

According to Fig. 10, it is found that voids and porosities in worn surface and around it are the main reason of creation of a delaminated layer which strengthens the possibility of delimitation mechanism theory in wear of these materials.

4. CONCLUSION

According to above-mentioned review, wear resistance of ADIs can be increased by the following methods:

1. Decreasing austempering temperature which through changing microstructure from upper bainite to lower one, UAV decrease and rise of fineness of ausferritic matrix can increase RWR.
2. Increasing austenitizing temperature to increase carbon content in retained austenite.
3. Selection of optimized austenitizing and austempering time to reach adequate amount of the retained austenite with high carbon content.
4. Increasing hardness of surfaces in contact with each other decreases wear process' destructive effects.
5. Decreasing solidification rate of castings in order to decrease nodule count of graphites in metallic matrix.
6. Determining of stress level of wear atmosphere; because in high stress wear processes, transformation of retained austenite to martensite has more effective role than bulk hardness of the sample. Therefore, in such a circumstance, high amount of high-carbon retained austenite will be useful and vice versa.
7. Increasing nodularity of graphite due to predominant wear mechanism.
8. Utilizing CADI and/or ACDI in order to introduce hard carbide particles to tough and ductile ausferritic matrix.

Moreover, wear processes in ADI parts which almost have sliding wear applications, commence initially with adhesive mechanism, and having produced wear debris continue with abrasive mechanism. Sever plastic deformation in surface and sub-surface layers causes to deform nodular graphites into oval ones, additionally, gathering of dislocations under the surface and consequently creation of microscopic holes. Microcracks nucleate from these stress concentration centers and reaching critical amount in size, the materials between surface of the sample and the crack will be separated under dominant delamination mechanism.

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