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EROSION OF DUCTILE CAST IRON WITH QUARTZ PARTICLES

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Original scientific paper

Ductile cast iron has high fatigue strength due to the spherical shape of graphite, especially after quenching and tempering. Higher toughness can be achieved by austempering. One of the advantages of ductile cast iron in relation to other cast irons is its good wear resistance. In the experiments, samples of ductile cast iron and austempered ductile cast iron were eroded with quartz sand particles at six different angles of impact (15°, 30°, 45°, 60°, 75° and 90°). The test results were presented as the loss of mass which occured during the test. Testing with quartz sand shows that the particle erosion resistance of ductile cast iron was better than that of austempered ductile iron for all impact angles except for 60°. The maximum measured wears of ductile cast iron and austempered ductile iron were at 75°.

Keywords: *austempered ductile cast iron, ductile cast iron, particle erosion*

Erozija nodularnog lijeva česticama kvarcnog pijeska

Izvorni znanstveni članak

Nodularni lijev ima veliku dinamičku izdržljivost zbog kuglastog oblika grafita, naročito nakon poboljšavanja. Visoka žilavost može se postići izotermičkim poboljšavanjem. Jedna od prednosti nodularnog lijeva u odnosu na ostale željezne lijevove je njegova dobra otpornost na trošenje. U ovom istraživanju ispitivana je otpornost na erozijsko trošenje nodularnog lijeva i izotermički poboljšanog nodularnog lijeva, česticama kvarcnog pijeska pri šest različitih kutova udara (15°, 30°, 45°, 60°, 75° and 90°). Rezultati ispitivanja prikazani su gubitkom mase tijekom ispitivanja. Rezultati pokazuju da nodularni lijev ima bolju otpornost na erozijsko trošenje od izotermički poboljšanog nodularnog lijeva pri svim kutovima udara osim kod 60°. Maksimalni gubitak mase kod oba materijala zabilježen je pri kutu upada od 75°.

Ključne riječi: *erozija česticama, izotermički poboljšani nodularni lijev, nodularni lijev*

1 Introduction
Uvod

Ductile cast iron is a cast, pseudo-binary iron-carbon alloy, with graphite mostly in spherical shape [1]. Ductile iron has high fatigue strength due to the spherical shape of graphite, especially after quenching and tempering. Ductile cast iron has good bearing properties and resistance to wear, corrosion and oxidation. Special properties (like resistance to aggressive media) can be achieved with alloying [2]. Austempering heat treatment significantly enhances the mechanical properties of ductile iron. Known as austempered ductile iron (ADI), this material offers improved strength and toughness in comparison to ductile iron [3].

The austempering heat treatment process consists of heating a material into the austenite phase field and then of quenching it to a lower temperature (the austempering temperature) and of holding it at this temperature to allow the austenite to transform isothermally to an acicular ferrite phase, known as bainite, which contains carbides [4]. Alloying additions can render ductile irons more suitable for commercial austempering because certain elements affect the solubility of carbon in the austenite, thereby influencing bainitic transformation [5].

The properties of austempered ductile iron (ADI) can be varied by changing the austempering temperature. A lower transformation temperature produces a fine, high-strength, wear-resistant structure. A higher transformation temperature results in a coarser structure that exhibits high fatigue strength and good ductility [6].

ADI has important advantages as its heat treatment time is short due to its chemical composition and microstructures and intricate shapes can be cast with strength and wear resistance properties similar to those of steels (with 10 % lower density). In addition, ADI is better than forged aluminium with respect to weight-strength ratio [3].

The improved mechanical properties achieved in austempered nodular iron could be exploited in the automotive industry by permitting cast component designs with reduced section size, thereby lowering vehicle weight, and by substituting ductile iron for steel in stringent engineering applications [7]. The major applications of austempered ductile iron include power plants, mining, railroad, automotive, military and agricultural industries [5]. ADI has become increasingly important for the manufacturing of components such as gears, crank shafts, cam shafts and rolls [8].

Wear is one of the most commonly encountered industrial problems, leading to frequent replacement of components [8].

Solid particle erosion is the loss of material that results from repeated impacts of small, solid particles. In some cases, it is a useful phenomenon, as in sandblasting and high-speed abrasive waterjet cutting, but it is a serious problem in many engineering systems, including steam and jet turbines, pipelines and valves carrying particulate matter, and fluidized bed combustion systems. Solid particle erosion can occur in a gaseous or liquid medium containing solid particles. In both cases, particles can be accelerated or decelerated, and their directions of motion can be changed by the fluid [9].

When the impact angle is low (between 0° and 30°), this kind of erosion is called the abrasive erosion. On the other side, if the impact angle is between 60° and 90°, the erosion is regarded as impact erosion [2].

Erosive wear occurs by plastic deformation and/or brittle fracture, dependent upon the material being eroded away and upon operating parameters. Ductile materials will undergo wear by a process of plastic deformation in which the material is removed by the displacing or cutting action of the eroded particle. In a brittle material, on the other hand, material will be removed by the formation and intersection of cracks that radiate out from the point of impact of the eroded particle. The shape of abrasive particles affects the pattern of plastic deformation around each indentation and, consequently, the proportion of the material displaced from each impact. In the case of brittle materials, the degree and severity of cracking will be affected by the shape of abrasive particles. Compared with more rounded particles, sharper particles would lead to more localized deformation and subsequent wear [10].

2 Laboratory investigations
Laboratorijska istraživanja

2.1 Materials description
Opis materijala

The experiment was performed on samples of ductile cast iron produced in the Split Shipyard. Samples of ductile cast iron were austempered at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. Parameters of austempering are shown in Figure 1.

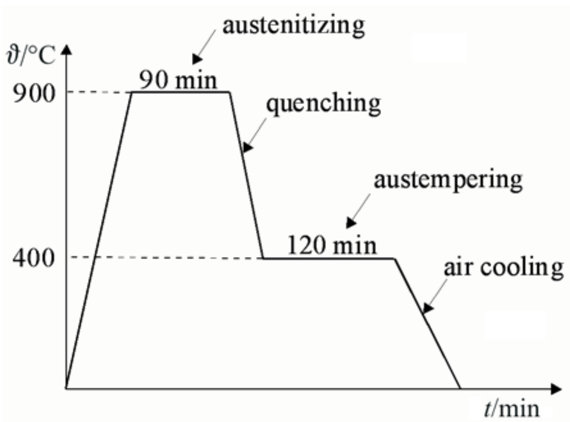

***Figure 1** ADI heat treat cycle*
***Slika 1.** Toplinska obrada izotermički poboljšanog nodularnog lijeva*

There are three phases to the ADI heat treat cycle: austenitizing, quenching and austempering. All three of these phases contribute to the final properties. First, the casting is heated to the austenitizing temperature. The rate of heating has very little or no effect on final properties. Then, the casting is held at this temperature until full austenitization is achieved. Full austenitization means conversion of the entire matrix to face centered cubic (FCC) austenite and the saturation of the austenite to carbon. The second phase of the heat-treat cycle is quenching. There are two criteria for a proper quenching: the cooling rate must be high enough to avoid pearlite formation during quenching and the desired austempering temperature must be reached in the casting prior to the beginning of the austempering reaction (ferrite nucleation).

The most important of the three phases of the heat-treat cycle is austempering. Both the temperature and the time duration of the austempering cycle have a strong effect on the matrix structure and the mechanical properties [11].

When ADI is austempered at lower temperatures, it has finer ferrite and austenite and this results in higher yield and tensile strength but with lower ductility. On the other hand, when ADI is austempered at higher temperatures, it has coarser or feathery ferrite and austenite and this reduces the yield and tensile strengths but imparts higher ductility [12]. The first temperature corresponds to lower bainite and the second one corresponds to upper bainite.

2.2 Chemical analysis
Kemijska analiza

A quantitative chemical analysis of ductile cast iron is performed by a spectrometer method on SPECTRUMAT-750 GDS Leco in the Laboratory for Metal Analysis at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb.

***Table 1** Analysis of chemical composition of ductile cast iron samples*
***Tablica 1.** Kemijska analiza uzorka nodularnog lijeva*

	Mass portion, %								
	C	Si	Mn	P	S	Cu	Ni	Mo	Mg
Ductile cast iron	2,34	2,72	0,72	0,054	0,011	1,14	0,095	0,016	0,033

2.3 Microstructural analysis
Analiza mikrostrukture

A microstructural analysis was performed in the Laboratory for Metallography at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. The microstructure of a ductile cast iron sample is shown in Figure 2a (ferrite-pearlite matrix) and the microstructure of an austempered ductile cast iron sample is shown in Figure 2b (bainite matrix).

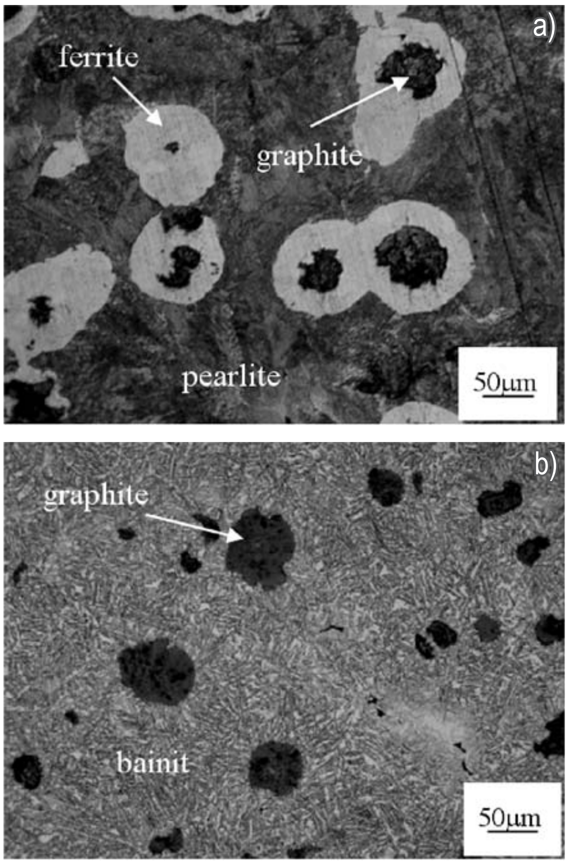

***Figure 2** Samples of a) ductile cast iron, b) austempered ductile iron*
***Slika 2.** Uzorci a) nodularnog lijeva, b) izotermički poboljšanog nodularnog lijeva*

The microstructure of ADI is upper bainite (it has coarser or feathery ferrite and austenite).

2.4 Hardness measurements
Mjerenje tvrdoće

Measurements of hardness were performed in the Laboratory for Testing Mechanical Properties at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. The hardness testing of samples was performed according to [13]. Results of the hardness testing are shown in Table 2.

Table 2 *Vickers hardness HV10*
Tablica 2. *Tvrdoće po Vickersu HV10*

	Ductile cast iron	Austempered ductile iron
1	240	243
2	297	306
3	254	279
4	258	279
5	283	247
6	240	270
7	283	297
8	258	287
9	283	287
10	287	292
$\overline{HV}$	268	279

There are no significant differences in Vickers hardness between ductile cast iron and austempered ductile iron samples.

2.5 Test of solid particle erosion resistance
Ispitivanje otpornosti na eroziju česticama

Wear resistance, is not an intrinsic property of the material but depends upon the tribological system, such as properties of materials tested, abrasive grit size, test condition, equipment, and environment [8].

In the literature on erosion, materials are broadly classified as ductile or brittle, based on the dependence of their erosion rate on. Ductile materials, such as pure metals, have a maximum erosion rate at low angles of incidence (typically 15° to 30°), while for brittle materials, such as ceramics, the maximum is at or near 90°. A variety of curves intermediate between these classical extremes exist and in some cases the same material exhibits behavior that shifts from one extreme to the other, depending on erosion conditions [9].

A test of solid particle erosion resistance, using rounded quartz sand as solid particles, was performed in the Laboratory of Tribology at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. The particle erosion tester is shown in Figure 3 (details are shown in Figure 4).

Figure 3 *Particle erosion tester*
Slika 3. *Uređaj za eroziju čestica*

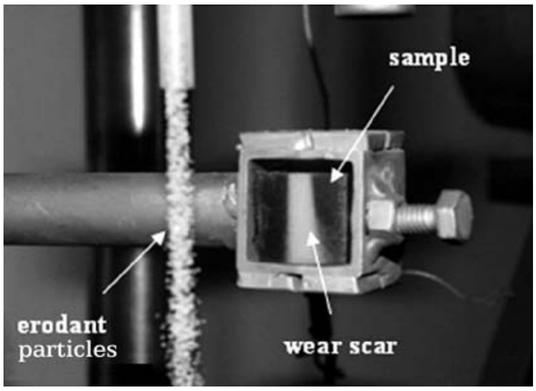

Figure 4 *Testing of solid particle erosion*
Slika 4. *Erozija krutim česticama*

Testing parameters:
- abrasive: rounded quartz grain sand AFS 50/70 (Figure 5)
- revolution: 1440 rev/min
- velocity of samples: 24,265 m/s
- time of testing: 13 min 53 sec
- number of impacts: ~20 000
- impact angles: 15°, 30°, 45°, 60°, 75° and 90°
- dimension of samples: 18×18×18 mm

Figure 5 *Erosion particles of quartz sand*
Slika 5. *Erozijske čestice kvarcnog pijeska*

Figure 6 shows results of particle erosion testing.

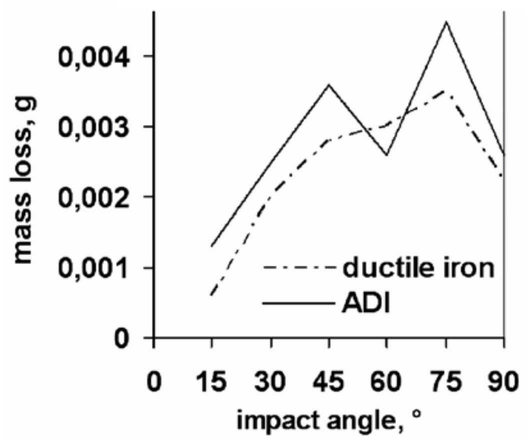

Figure 6 *Mass loss of ductile cast iron and austempered ductile iron (ADI) samples*
Slika 6. *Gubici mase uzoraka nodularnog lijeva i izotermički poboljšanog nodularnog lijeva (ADI)*

Figure 6 shows that particle erosion resistance of ductile cast iron was better than that of austempered ductile iron for all impact angles except for 60°. Ductile cast iron and austempered ductile iron curves have maximum value at 75°. It was considered that a huge part of the impact energy is spent on the formation of plastically deformed material regions on the surface of ductile iron and is absorbed by its high toughness. Austempered ductile iron has a double-peak erosion curve with fall in erosion at 60°. The martensite and carbides that embrittle the sample could induce the peek found at high angles (75°) to occur by brittle erosion [14]. This ADI sample, will be used as an example to discuss the wear observations for double peak curves (45° and 75°).

2.6 Wear surface analysis
Analiza trošene površine

In order to examine the erosion mechanism and damages, top-view of the eroded surfaces of the samples structure were observed by Scanning electron microscopy (SEM).

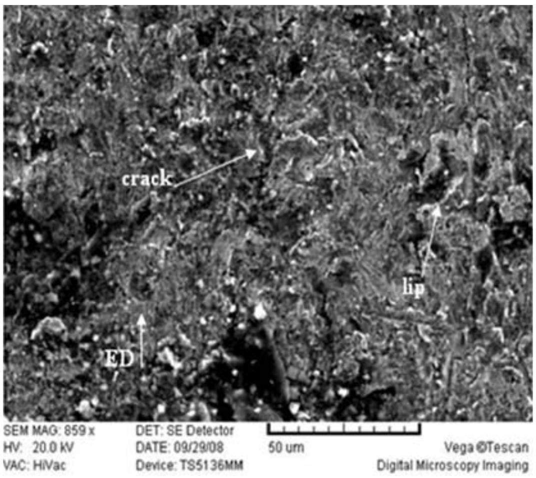

Figure 7 *Wear surface of ductile cast iron (ED – erosion direction)*
Slika 7. *Trošena površina nodularnog lijeva (ED – smjer erozije)*

When the impact angle exceeded 45°, erosion cracks were observed in the erosion surface of ductile iron samples. However, the erosion cracks were not observed for low impact angles (< 45°) and for high impact angles (>75°) for ductile iron samples. The appearance of the erosion surface (45° impact) shown in Figure 7.

At oblique impact angles (30° and 60°), a hard erodent causes plastic flow in a relatively soft surface of ductile iron and material removal occurs by microcutting and microploughing (see Figure 7).

Grooves and lip mechanism were observed on the wear surface (see Figure 8a i 8b). The martensite phase of ADI results in large brittle cracks in the oblique wear surface (shown in Figure 8). The increased brittleness caused by the martensite not only reduced erosion resistance but also created the erosion peak at 75°.

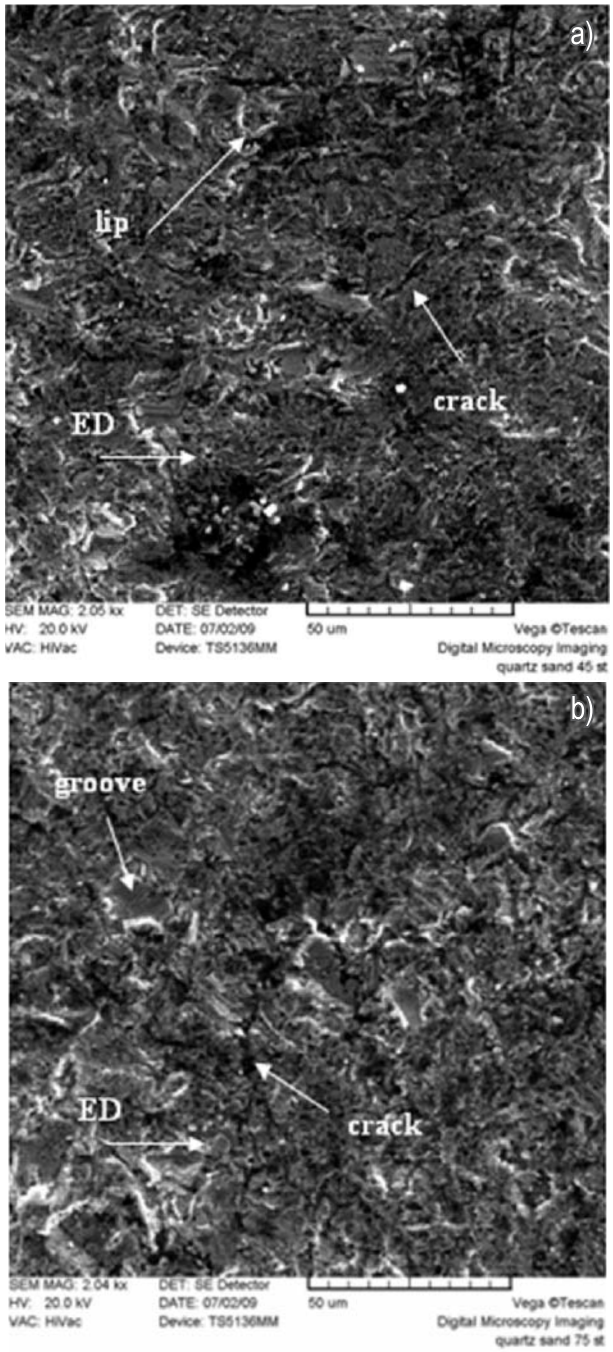

Figure 8 *Wear surface of ADI: (a) 45°, (b) 75°*
Slika 8. *Trošena površina izotermički poboljšanog nodularnog lijeva: (a) 45°, (b) 75°*

Figure 9 shows that nodular graphite appeared in the eroded surface at impact angle of 15°. When increasing the impact angle, nodular graphite becomes less visible.

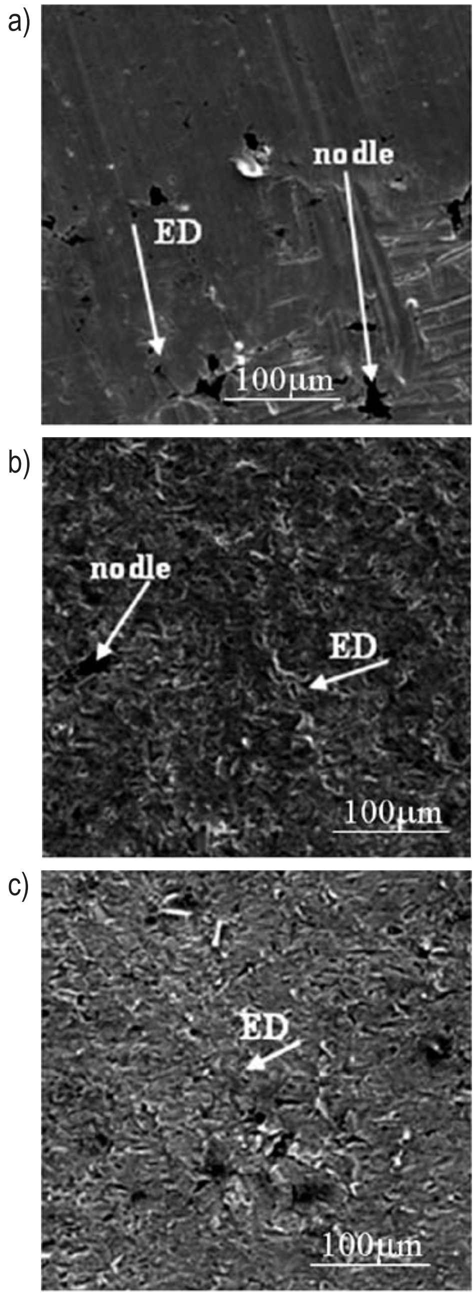

Figure 9 *Sample surfaces of ductile iron eroded at impact angle: a) 15°, b) 30° c) 45°*
Slika 9. *Površina uzorka nodularnog lijeva erodiranog pod kutom od: a) 15°, b) 30° c) 45°*

The stream of erodant particles seemed to have striked out some nodles of graphite and covered the by iron matrix. During the erosive wear process at oblique impact angles, the nodular graphites are deformed by impingement and ploughed out. The shallower nodular graphite is shown to be more deformed and has been found to play a role in crack nucleation. This effect leads to crack formation towards the eroded surface. Nodular graphites are bent in the direction of impact in the severely deformed areas just below the eroded surface.

3 Conclusion
Zaključak

One of the advantages of ductile cast iron in relation to other cast irons is its good wear resistance. However, it must be considered that wear resistance depends on wear condition. Solid particle erosion resistance is function of impact angle. Testing with quartz sand shows that the particle erosion resistance of ductile cast iron was better than that of austempered ductile iron for all impact angles except for 60°. Microstructure of tested austempered cast iron was upper bainite whose main characteristics are high fatigue strength and good ductility (not wear resistance). The maximum measured wears of ductile cast iron and austempered ductile iron were at 75°. Austempered ductile iron has a double peak erosion curve with a fall in erosion at 60°.

The stream of erodant particles striked out some nodles of graphite and covered the place where it was by iron matrix. When increasing the impact angle, nodular graphite becomes less visible. Erosion cracks, lips and many grooves were observed in the erosion surface of all samples.

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