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The contact fatigue and the wear of DADI class aluminum cast iron

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Abstract

In the present work there are given the results of experimental investigations of contact fatigue and the wear of deformable high strength ADI (DADI) class aluminum cast iron depending on the phase ratio in metallic matrix. It is shown that: Modification of cast iron melt with the magnesium vapor gives the opportunity the low silica (0.5-0.7% Si) high strength cast iron to be received, in which the concentration of sulfur will not exceed 0.002%. Besides, the type and degree of austenite transformation of the received cast iron can easily be varied so that required ratio of phase components such as upper bainite, lower bainite, martensite, carbide and the retained austenite could be provided in the metallic matrix and therefore the hardness in the range of 30-57HRC can be given. The wear rolling and rolling with creep tests carried out on the specimens tempered till different levels of hardness showed strong dependence of contact fatigue and the wear on the amount of retained austenite in the samples with optimal ratio, required for keeping the high wear resistance of wearing surfaces, of bainite and martensite phase components in the matrix structure. The stated parameters of the contact fatigue and the wear gives us reason to treat the high strength DADI class aluminum cast iron as an efficient substitute for the expensive steel as a constructional material for manufacturing the critical parts for high pressure multistep gas pumping compressors.

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1. Introduction

The modern industry is inseparably linked with such construction materials as steel and cast iron, and this trend will be kept for the foreseeable future. It should be mentioned that during the last decade the interest in the high-strength cast iron with the globular graphite as to the new class of the construction materials have been rose. The volume of the worlds manufacturing of cast products made of given material constantly grow, but its utilization in the serial production is yet considerably limited due to the strict requirements towards the casting quality and insufficient awareness on the features and the technology of austempered ductile iron (ADI). Realization of the potentially big economy of the recourses by substitution of steels for the relatively cheap high-strength cast iron of class ADI is embarrassed also by the fact that till nowadays there are non of technologies which would turn this casting material simultaneously to the material which can be treated by pressure for the formation of blanks and parts using such effective methods of secondary formation as hot rolling, pressing, stamping, extrusion and others.

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We have developed new compositions of bainite and martensite strengthened aluminum low-silicon cast irons of class ADI, which had unprecedented high deformability for this class of cast irons, in the temperature range of 850-950°C [1-3]. It was shown that important feature of this kind of plastically deformable ADI (DADI) is high degree deformability of spherical graphite inclusions together with metallic matrix. Utilization of technology of cast iron melt’s spheroidizing treatment directly using the magnesium vapors [4] allowed us to meltdown also high-silica cast irons with low (in comparison with conventional ADI) Mo and Cu content in which the concentration of sulfur was less than 0.002% and the mentioned high-silica cast irons also had the same deformability in the range 850-950°C and due to DADI’s close to the steel’s properties it is quite promising to give the high affordability in case of its application instead the construction steels.

The accumulated global knowledge in this field, shows that the quality maintenance, high-level physical and mechanical properties and performance parameters of the end product made of the cast irons with nodular graphite, in general, (to which our material belongs), mainly depends on the technology of preparation of liquid melt, spheroidizing technique and heat treatment of ingots. Moreover, the most important technological operation is inoculation of the melt. The latter consists in the liquid melt treatment, mainly with magnesium or magnesium-containing ligatures. This technique is extremely complex, unstable and decisively influences on microstructure and physical properties of the cast. The technologies of high-strength cast iron production differ between each other because of the variety of inoculators and the methods of their inoculation.

Existing data of the high-temperature (1000°C) plastic deformation influence on the structure formation in austenite ADI during austempering [5] cannot be used as scientific basis for the practical realization of idea about possibility of combination the high-temperature thermo-mechanical treatment (HTTMT) directly with austempering into the unified technological cycle of the detail secondary formation out of ADI.

In the present work there are given the results of experimental investigations of contact fatigue and the wear of deformable high strength ADI (DADI) class aluminum cast iron depending on the phase ratio in metallic matrix.

2. Experimental Procedure

For the experiments there was cast low-silicon containing aluminum (2%Al) ADI class cast iron. The experimental heats performed in a 40 kg medium frequency induction furnace. The modification of the melt was conducted directly by magnesium vapors using the original modifiers [6]. The initial specimens for the further thermo-mechanical treatment and for the different austempering regimes were cast in the form of Y-blocks.

The wear experiments using rolling friction ware operated by the wear testing facility in which 50 mm diameter and 10 mm thick circular specimen of the investigated alloy was loaded by the force 100 N to the rotating with the frequency 10Hz counter body which had the same shape and dimensions and was made from steel U8. One set of the specimens was tested just in rolling conditions whereas another one under that of the rolling+20% sliding. There were utilized counter bodies of different hardness: 43, 51 and 55 HRC. The circular specimens of the investigated alloys were prepared out of the cast blanks and also out of bars obtained due to the hot rolling of cast blanks. Hot rolling was done at 920°C along the longest dimensions of the starting material with the total deformation of ~30% (15%÷15% reverse rolling with velocity of 0.35m/sec).

The initial specimens prepared using the mentioned method afterwards the austenization at 900°C-60 min have passed the multistep isothermal hardening in order to form in them required ratio and sequence of the phase transformation products (lower bainite, upper bainite, tempered martensite and retained austenit) development. Chosen schemes of the thermo- and thermo-mechanical treatments allowed us to obtain the specimens with required hardness in the range of 39 ÷ 57 HRC.

The initial effective rolling surfaces of the investigated rings and of the counter body were the surfaces treated by the grinding lap with the abrasive graininess of 20÷10μ. The topography and fine structure transformations of the surface area on the different wearing stages (after each 30 kilometer rolling cycle) were investigated by the SEM. Quantity of the retained austenite was determined using standard X-ray method. The base composition (wt. %) of the investigated alloy as determined by emission spectroscopy are shown in Table1.

An original technique of liquid cast iron’s modification with magnesium vapor, ensuring 80% consumption of Mg and 95% spheroidizing of the graphite that forms a background of technology for production of new compositions of low-silicon aluminum-containing, DADI with low content of sulfur (<0.002%).
Table 1. Chemical composition of the investigated alloy

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>Mo</th>
<th>Cu</th>
<th>Al</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>3.63</td>
<td>0.84</td>
<td>0.38</td>
<td>&lt;0.002</td>
<td>-</td>
<td>-</td>
<td>2.0</td>
<td>0.041</td>
</tr>
</tbody>
</table>

The new regimes of heat treatment and high-temperature thermo-mechanical treatments (HTTMT) of DADI were providing purposeful regulation of phase composition (lower bainite, upper bainite, tempered martensite and retained austenite) of metallic matrix, keeping hardness of ingots and end products at desirable level within the range of 38 ÷ 60HRC and increase in fatigue strength for ~15%. As a result we are able to produce the new high-strength cast irons with the unprecedented, for the ADI cast irons, high level of deformability (up to 70% totally) in the temperature range of 850 ÷ 950°C. Samples for laboratory characterizations of dry frictions were also prepared. The tests have shown that the developed technique of liquid melt modification with Mg vapor provides a statistically uniform distribution of graphite nodules in ingots (with the thickness of walls 1 to 150mm), and ultra-low content of Sulfur (<0.002%). The combination of high-temperature thermo-mechanical treatment (HTTMT) and austempering process (ADIzation) was accomplished in single step for the first time in order to govern and refine performance parameters of components produced from the developed DADI. The results of the conducted experiments show that various schemes of HTTMT+ADIzation combinations may be successfully used for improvement of fatigue and wear resistance of the components made from DADI via direct casting and deformation of the cast as well.

3. Results and Discussion

Flaking is known as the most expanded form of spalling of rolling metallic elements and the hardness is one of the most significant metal properties, resisting its friction, wear or plastic deformation [7]. Although for natural composite, e.g. ADI, which must be considered as a system (the metallic base one with nonmetallic inclusions) the wider complex of parameters must be taken into account when solving problems of controlling friction and reducing wear of the machine elements [8]. Together with the hardness of metal matrix (controlled by phase composition and dispersivity of phase components) it is necessary to control the size, shape and character of the distribution of graphite nodules as well as their boundaries with metal matrix achieving wide spectrum of properties of ADI articles. One of the effective ways for reaching this goal is investigation of DADI behavior at friction while changing these parameters. Rolling wear test results of cast and hot-rolled specimens of studied alloy A-1 depending on the ratio of phase components in metal matrix and the ratio of hardness of specimen and rolling agent in tribosystem are given in the Table 2.

Table 2. Rolling and 20% sliding wear test results and the structure influence data obtained during dry friction of the investigated alloy

<table>
<thead>
<tr>
<th>Kind of Treatment</th>
<th>Structural composition* of matrix, %</th>
<th>Hardness, HRC</th>
<th>Wear rate, mg/km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sample Running-in stage</td>
<td>Rolling+20 % Sliding</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rolling agent</td>
<td>Running-in stage</td>
</tr>
<tr>
<td>Austempering</td>
<td>1 75LB+15Mt+10Ar</td>
<td>54 51</td>
<td>0.767 0.135</td>
</tr>
<tr>
<td></td>
<td>2 45Mt+40LB+15Ar</td>
<td>52 55</td>
<td>0.713 0.102</td>
</tr>
<tr>
<td></td>
<td>3 80LB+20Ar</td>
<td>57 43</td>
<td>0.200 0.097</td>
</tr>
<tr>
<td>HTTMT</td>
<td>4 55LB+15Mt+30Ar</td>
<td>39 51</td>
<td>0.460 0.200</td>
</tr>
<tr>
<td></td>
<td>5 50Mt+25LB+25Ar</td>
<td>48 55</td>
<td>0.400 0.040</td>
</tr>
<tr>
<td></td>
<td>6 75LB+25Ar</td>
<td>40 43</td>
<td>0.280 0.090</td>
</tr>
</tbody>
</table>

* - LB – Lower Bainite; UB – Upper Bainite; Mt – Tempered Martensite; Ar – Retained Austenite.

This data presented was obtained as a result of the laboratory tests on the 30% deformed new material investigated during rolling and 20% sliding wear rests under the 100N load, 10Hz rotation frequency and the specimens were run for 120km. From the displayed data the following evident conclusions may be inferred: 1. HTTMT treatment combined with multistep austempering significantly improves wear resistance of aluminum DADI; 2. Multistep austempering process is an effective method for controlling ADI properties.
The analysis of weight loss experimental fall data showed that friction process must be demarcated as running-in and stationary stages. It is evident that on both stages structurally sensitive processes takes place: running-in process mostly depends on initial working surface condition of specimen and stationary wear stage basically depends on the testing specimen’s properties. These conclusions and assumptions are proved by SEM observations of functioning surfaces of the studied specimens.

SEM images of initial ground surfaces of A-1 alloy specimens, treated by different kind of treatment (Table 2) for achieving various values of hardness are displayed in Fig.1. a-d. It is obvious that, after mono-directional grinding using the lap disc (with abrasive grain size of $20 \div 10 \mu m$), in all cases the specimen surface morphology has complicated relief profile. There are clearly visible parallel scratches, grooves with torn edges, asperities, tearing areas and flat, licked by plastic flow, microchannels and microcracks.

In this case, the surface profile differences of observed roughness are $\leq 10 \mu m$. Also certain peculiarities are observed while studying ground surface morphologies according to the material hardness of cast and hot-rolled specimens. In the first place it is exposed in graphite nodules and its close metal matrix condition. Namely, in the high hardness specimens graphite nodules are “cut” by grinding surface while grinding process Fig. 1. a,b. But while grinding of comparative low hardness cast and hot-rolled specimens graphite nodules are completely rubbing by plastic flow of metal matrix and they are not observed on surface SEM images (Fig. 1. c,d).

Evidently, different structure of initial surfaces in combination with hardness will have significant role especially on the running-in stage of rolling friction wear.

In the Fig.2 SEM images of high-strength (51 HRC and more) A-1 alloy cast specimens worn surfaces are displayed. Their hardness was achieved by various thermal treatment kinds (kinds I, II and III in the Table 2). SEM images of surfaces of these specimens formed at running-in stage while rolling friction with rolling agent of various hardness (with lower and higher hardness from that of samples) correlate with experimental weight loss data of the same samples (Table 2) and accentuate significant role of phase-composite configuration of metal matrix in high wear resistance of ADI while rolling dry friction.
From these data may be concluded that for ADI parts intended to work in friction units lower bainite structure with corresponding ratio of retained austenite and tempered martensite is available.

Fig. 2. SEM images of worn surfaces of cast samples A-1 alloy formed after rolling with rolling agent of different hardness: a,b) sample - 57 HRC, rolling agent - 43 HRC; c,d) sample - 54 HRC, rolling agent - 51 HRC; e,f) sample - 52 HRC, rolling agent - 55 HRC.

The new high-strength deformable cast irons of ADI type (DADI) are applicable for the production of critical parts used in machine building by casting and by hot working of casing blocks. This provides substitution of steel parts, improvement of quality and lifetime of the final products, reduction in metal consuming and in price.

The developed composition of the new modifier (conditioning agent) and the technique of its input in liquid melt for its modification by pure Mg vapor allows producing high-quality cast from low-silicon cast iron of ADI-type without using of expensive ligatures as well.

The technology of ADI melting, using the developed modifier (conditioning agent), decreases the final product price not only because of energy-saving technology of smelting but also because of the possibility to repeatedly use the foundry waste and swarf, excluding desaturation of the melt by steel, which increases price of the final product.

Our works have both, the technological background for practical realization of the idea of HTTMT of ADI to convert it into a technological solution addressed to metal forming operations for production of various precise machine parts from DADI instead of steel which is currently used in contemporary machine-building.

4. Conclusions

It is established that, for the investigated composition of ADI it is revealed the possibility of control by the degree and mechanism transformation of retained austenite in the intermediate temperature range; the optimum combination
of high strength and good wear resistant end contact fatigue properties of ADI is caused by the ultrafine bainite structure dispersion of its microstructure and the variable content of retained austenite.

The investigation showed strong positive influence of combined use of multistep austempering processes and HTTM treatment on the wear of low silicon aluminum containing ADI class cast iron.

Obtained results can be used for establishing the background for practical realization of the idea of HTTMT of ADI and convert it into the technological solution addressed to a metal forming technological operation for production of various precise machine components from DADI instead of steel products which are used in machine building. We can conclude that it is possible for this type of material the purposeful control of the phase value, ratio and the dispersion, and this in its turn allows the increasing of resistance against the fatigue due to the prevention of the furrows and grasping between wearing surfaces. Here the important point is that the wear resistance of the material depends not only on its hardness property but also there is a strong dependence on the investigated materials surface layers resistance against the fatigue and thus it is evident that both of the structures are the sensitive parameters and hens the purposeful controlling of the structure in the DADI class cast irons, as an effective substitution material for the steel, would be one of the important technical and technological tasks.

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References