Role of Matrix Structure on Impact-Wear Resistance of As-Quenched 27%Cr Cast Iron

Ngo Huynh Kinh Luan1, Koreaki Koizumi1, Kuniaki Mizuno1, Yutaka Yamada1, Tetsuya Okuyama2 and Masaru Nakayama3

1Joh Kikoh Co. Ltd., 476-0001, Japan
2Department of Materials System Engineering, National Institute of Technology, Kurume College, Kurume 830-8555, Japan
3Department of Materials Engineering, National Institute of Technology, Kurume College, Kurume 830-8555, Japan

The role of retained austenite and martensite on impact-wear resistance of 27%Cr cast iron quenched at temperatures of 1223 K and 1423 K was investigated at various impact angles by impact wear tests using an air blasting machine. Measurement of the hardness and volume fraction of martensite in the matrix of both samples as well as SEM observation were performed. Quenching treatment at 1223 K resulted in a higher volume of initial martensite in the matrix, and wear rate reached maximum at 60°. On the contrary, the matrix with a high volume of retained austenite obtained by quenching at 1423 K showed a maximum impact-wear rate at 45°. The difference in the wear resistance between the two types of as-quenched samples can be explained by the transformation from metastable austenite to strain induced martensite and self-tempering of the initial martensite occurring under impact wear environment. As the volume of retained austenite increases, hardening due to strain induced martensite was found to overlap with softening due to tempering of the initial martensite, which contributed to the suppression of the wear rate. 


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Keywords: 27%Cr white cast iron, retained austenite, martensite, impact-wear resistance, impact angle

1. Introduction

Cast irons with a Cr content of 25 to 30% which have excellent impact-wear resistance are widely used as parts inside shot blasting machines or surface treatment equipment such as blades, liners and distributors.1) Conventionally, many works in literature have reported that under an environment in which abrasives media continuously collide with the surface of material, its wear resistance depends on various factors such as impact conditions (pressure, velocity), microstructure as well as properties of abrasive media.2–5) Additionally, it has been stated that there is a completely different dependence of wear rate on impact angle between ductile and brittle materials.6,7) For example, there is a trend that SUS304 stainless steel, one of ductile metals, shows peak in wear at low impact angles between 30 and 50°, whereas maximum wear rate occurs at an impact angle near 90° in case of brittle materials such as glass and ceramics. For high Cr cast irons, most studies have focused on clarifying how primary carbides affect their wear resistance by adding carbide-forming elements such as Mo, V and W individually or in combination.8–10) However, there are few reports on the role of constituent phases in matrix such as austenite and martensite on the wear behavior. In our previous paper, quenching heat treatment at the temperature above 1323 K was found to result in improvement of wear resistance of 27%Cr cast iron as compared with as-cast sample, when impact-wear test was performed at 90°.11) However, in the actual usage environment of shot blasting machines, impact angle of abrasive media with respect to the wear-resistant parts is not limited to 90°, but of course, at various angles. So it is necessary to further clarify how retained austenite and martensite in matrix play a role in the impact wear mechanism when the impact angle changes.

Therefore, in this study, we compared the wear of this cast iron at various impact angles, which matrix mainly consists of retained austenite or martensite by quenching at high or low temperature, and then investigated the relationship between microstructure and impact wear characteristics.

2. Experimental Procedure

2.1 Sample preparation

A bulk plate with dimensions of 220 mm × 180 mm × 12.5 mm, one of the assembly components of the surface treatment machine was employed to investigate the characteristic of impact wear of 27%Cr white cast iron. Raw materials were melted in a high frequency introduction furnace and poured into the alumina sand molds to produce the plates. The chemical compositions of the experimental cast iron are listed in Table 1.

Cutting from the as-cast plate using a wire cutting machine, samples with dimensions of 50 mm × 55 mm × 12.5 mm were heat-treated in an electric box furnace at two temperatures of 1223 K and 1423 K for 3.6 ks followed by forced-air cooling. Two types of as-quenched samples, namely 1223 K AsQ and 1423 K AsQ, were used as objective samples in impact-wear test. In order to avoid the influence of decarburization layer, all samples were mechanically ground about 0.5 mm for removal of surface layer prior to the impact-wear test.

Table 1 Chemical compositions of cast iron (mass%).

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.93</td>
<td>0.52</td>
<td>0.85</td>
<td>0.022</td>
<td>0.012</td>
<td>0.85</td>
<td>26.82</td>
<td>0.22</td>
<td>bal.</td>
</tr>
</tbody>
</table>

*This Paper was Originally Published in Japanese in J. JFS 93 (2021) 462–469. Some spelling errors were modified.
2.2 Impact wear test

The impact-wear resistance of two as-quenched samples was evaluated based on the results of weight loss obtained by using the air blast machine. For comparison, as-cast samples were also tested at the same conditions. In this study, impact-wear test was carried out by changing the angle under adjustment of nozzle position with respect to objective sample, as illustrated in Fig. 1(a). The distance between nozzle tip and sample was a certain distance of 100 mm. Impact angle (θ) was defined as the incident direction of abrasive media from the nozzle with respect to the sample surface, and the tests were performed under three impact angles of 30, 45, and 60°. Under each condition, 25 kg of iron grit (Fe–0.6Cr–1.0C) with an average diameter of 1.2 mm were accelerated by the injection of 0.5 MPa compressed air from a 6 mm diameter nozzle tip to collide with the sample surface. The test time for each cycle was 1.0 ks. Weight loss measurement was carried out using an electric balance to evaluate impact-wear resistance every 5 cycles. Test cycles totaled 20, but the test would stop if a through hole appeared in the sample. During this test, regardless of angles, it was visually observed that a large number of sparks were generated when iron grit collided with the sample surface, as seen in Fig. 1(b). The dependence on impact angle of wear resistance in this study was comprehensively assessed together with the results at 90° reported in the previous work.11)

2.3 Microstructural analysis

Microstructures of as-quenched samples were examined using a JEOL IT-100LA scanning electron microscope (SEM) equipped an energy dispersive X-ray detector (EDS). The backscatter mode of SEM was used to observe microstructure near worn surface. Volume fraction of martensite at 10 locations were measured using a Fischer FMP 30 feritscope before and after the impact-wear test.

2.4 Hardness measurement

Bulk hardness was measured using a Vickers hardness tester (Akashi, AVK-A) with a load of 30 kg and dwell time of 15 seconds. The average of 10 measurements was taken as the hardness of sample. For investigation of hardness profile from surface to center of sample, hardness measurement was performed using a Micro Vickers hardness tester (Shimadzu Corporation, HMV-G21FA) under a load of 0.3 kg. Each value in the hardness profile was calculated from three measurements. Also, regions which consisted of only matrix with secondary carbides were conducted on the same tester with a load of 0.1 kg.

3. Experimental Results

3.1 As-quenched microstructures and hardness

Microstructures of experimental cast iron after quenching heat treatment at 1223 K and 1423 K are shown in Fig. 2. Both samples consisted of primary M7C3 and M23C6 type carbides surrounded in austenitic and martensitic matrix. As indicated by black arrows, there is a difference in secondary carbide size due to variation in quenching temperature. It is recognized that numerous fine secondary carbides with a
mean size of less than 1 µm disperse in matrix of 1223 K AsQ sample. On the other hand, coarsening of secondary carbides is apparent in 1423 K AsQ sample, but their number becomes smaller than 1223 K AsQ one. Martensite volume is 41.9% for 1223 K AsQ sample and 9.8% for 1423 K AsQ one. This implies that martensite becomes more stable by quenching at low temperature.

Hardness of 1223 K AsQ and 1423 K AsQ samples are 770 HV and 654 HV, respectively. The values are in good agreement with the microstructures of as-quenched samples.

3.2 Relationship between weight loss and impact angle

The cumulative weight loss of as-quenched samples during the impact-wear test for each impact angle as a function of test cycle are summarized in Fig. 3. For comparison, weight losses of as-cast samples are also shown in the figure. For 1223 K AsQ samples, hole penetration due to the collision of iron grit appears earlier than other samples, so the tests stopped at 13 cycles for 60°, and 18 cycles for 90°. It can be seen from the figure that increment of weight loss becomes larger in order 1423 K AsQ, as-cast and 1223 K AsQ samples. The tendency does not change even when performed at four impact angles. In detail, weight losses of 1223 K AsQ samples tend to increase exponentially at all angles, whereas 1423 K AsQ samples show a linear increase in weight loss up to 20 cycles. Regarding as-cast samples, weight losses increase exponentially, but their curves are not as remarkable as 1223 K AsQ samples. Also, weight losses for 45° and 60° are larger than 30° and 90°.

From the above results, impact-wear resistance for experimental cast iron can be ranked in increasing order of quenching at low temperature (1223 K), as-cast, quenching at high temperature (1423 K).

Next, the results obtained after 15 cycles were extracted for assessment of the relationship between wear resistance and impact angle. Because the data for 1223 K AsQ sample impacted at 60° could not be acquired, the extrapolated value of 30 g estimated from the weight loss curve was used. Figure 4 shows the dependence of weight loss for 15 cycles on impact angle. It is found that 1423 K AsQ and as-cast samples display a maximum wear at 45°, different from the 1223 K AsQ sample (at 60°). Such a difference is also observed in ductile metals and brittle materials. Therefore, it is expected that the difference in wear behavior of experimental cast iron relates to the dissimilarity of structural matrix. With respect to evaluation of wear properties of 25~27%Cr cast irons tempered, many researchers suggested that 60° was the angle at which wear is most remarkable under impact-wear environment.9,10) However, the results
obtained in this study are inconsistent with those results. The reason why such an angle exhibits most severe wear is attributed to relate to the volume ratio of metallic phases in matrix, i.e. retained austenite and initial martensite. This will be discussed in detail below.

Photographs of the worn surfaces for all samples after impact wear test are displayed in Fig. 5. It is seen that the damaged area of 1223 K AsQ samples is much wider than 1423 K AsQ samples even under the same test conditions. Here, the configuration of damaged surfaces are examined in detail. First of all, from the results of 1223 K AsQ samples, it could be confirmed that the shape of damaged surface varies with impact angle. The remaining wear marks of 1223 K AsQ samples at 30° and 45° look like a spoon-shaped dent, unlike through holes formed at 60° and 90°. On the other hand, it is also observed that shape change for 1423 K AsQ samples has a similar tendency, but the shape of wear marks is a quite narrow area. In order to clarify the difference, as indicated by black arrows in the figure, areas where wear occurred remarkably were extracted, and SEM observation was performed at the interface between the place of little wear and the place of heavy wear. The obtained results are displayed in Fig. 6. As shown, many flakes adhering to the surface could be detected at any impact angle. Observation of the entire surfaces revealed that the maximum area of flakes and their number varied with impact angle. The number of flakes tended to increase highest at 60° for 1223 K AsQ sample but at 45° for 1423 K AsQ and as-cast samples. Besides, the maximum area of flakes was about 100 to 200 µm² in all the samples. Comparing the worn surface roughness of three types of samples, it is obvious that there is a difference in surface feature: ripple patterns appear on the worn surface for 1223 K AsQ samples, whereas 1423 K AsQ and as-cast samples have relatively smooth surfaces.

4. Discussion

It is generally known that alloying elements are heterogeneously distributed and micro-segregated in the matrix of as-cast state, unlike quenching. Therefore, only as-quenched samples were discussed in order to clarify how their microstructures affect the wear behavior.

Cutting in half for two types of 1223 K AsQ and 1423 K AsQ samples after wear tests performed at three impact angles, the cross-sectional microstructures below worn surfaces were observed. Figure 7 displays the results of
SEM observation at low magnification of these samples. It is obvious that there is a difference in roughness of damaged surfaces due to variation in quenching temperature from the cross-sectional view. In comparison with 1423 K samples, the wavy rough surface step for 1223 K AsQ samples is larger. Particularly, surface roughness becomes more significant at an impact angle of 60°.

In order to investigate the microstructure of the worn part in detail, the areas close to the worn surface were subjected to SEM observation. The enlarged microstructure are shown in Fig. 8. It is found that there are many cracks inside primary carbides in all samples. Additionally, it seems that the primary carbides deform together with the matrix near the worn surface. Observation of flakes adhering to sample surface revealed that flakes have various shapes and their thickness varies depending on their positions. For 1223 K AsQ sample impacted at 60° which is most worn, the maximum thickness of the flake is about 25 µm. It should be noted here that the microstructure of flake differs entirely from matrix in both of 1223 K AsQ and 1423 K AsQ samples regardless of impact angle. No primary carbides, but only fine carbides are detected to exist in flakes. As indicated by white arrows, these flakes do not completely adhere to the sample surfaces, and crevices are observed. Therefore, 1223 K AsQ sample impacted at 60° and 1423 K AsQ sample impacted at 45° of which wear rates are most remarkable, were employed to investigate that the regions where flakes still attached matrix and primary carbides. Figure 9 shows the high magnification observation result and EDS composition mapping of the area indicated by square frames in the corresponding SEM images (Fig. 8). For 1423 K AsQ sample, primary carbides in matrix near the surface have already fractured. Some of them are observed to be laterally displaced and sheared at the boundary as indicated by white arrows. Such a region is recognized to exist locally below the impacted surface in not only 1423 K AsQ sample but also 1223 K AsQ one. EDS composition mapping shows that alloying elements in flakes are mainly Fe and C. Cr content in the flake is obviously lower than that in matrix in samples. The quantitative analysis results of matrix and flakes are summarized in Table 2. The results of iron grit before and after experiments for 1223 K AsQ and 1423 K AsQ samples are shown in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Impact Angle</th>
<th>1223 K AsQ</th>
<th>1423 K AsQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8 Cross sectional microstructures below most worn surfaces.

Fig. 9 High magnification SEM images and EDS compositional mappings of flake and matrix in 1223 K AsQ sample impacted at 60° and 1423 K AsQ sample impacted at 45°.
Table 2: EDS analysis results of microstructure of 1223 K AsQ, 1423 K AsQ samples and iron grit (mass%).

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1223 K AsQ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td>0.92</td>
<td>16.01</td>
<td>bal.</td>
</tr>
<tr>
<td>Primary carbide</td>
<td>-</td>
<td>59.98</td>
<td>bal.</td>
</tr>
<tr>
<td>Flake</td>
<td>0.60</td>
<td>1.82</td>
<td>bal.</td>
</tr>
<tr>
<td>1423 K AsQ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix</td>
<td>1.03</td>
<td>15.23</td>
<td>bal.</td>
</tr>
<tr>
<td>Primary carbide</td>
<td>-</td>
<td>54.10</td>
<td>bal.</td>
</tr>
<tr>
<td>Flake</td>
<td>0.99</td>
<td>1.89</td>
<td>bal.</td>
</tr>
<tr>
<td>Iron grit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>0.64</td>
<td>0.76</td>
<td>bal.</td>
</tr>
<tr>
<td>After 20 test cycles</td>
<td>0.70</td>
<td>0.75</td>
<td>bal.</td>
</tr>
</tbody>
</table>

Fig. 10: Increased volume fraction of martensite in two types of samples after impact-wear test.

The reason for this is still unclear.

After impact-wear test are also shown for reference. It can be seen that the compositions of iron grit are almost similar. This implies that the compositions of iron grit do not changed due to impact wear test. However, Cr content in the flake adhering to each sample is about 1.9 mass%. The value is higher than iron grit, but much lower than that of matrix and primary carbides. From this result, it is presumed that the flake adhering to the worn surface is a melt of iron grit. Formation of the melt can be estimated as follows. When iron grit collides with the surface of objective sample, the shape of grit is so small that impingement heat generated is easily conducted the entire grit, which is considered to cause melting. As these melts of iron grit adhered to the surface, alloying elements such as Cr from a local place on the sample surface were presumed to diffuse inward the melts. Besides, taking into consideration the spark generation shown in Fig. 1 and analysis results of the alloying elements shown in Table 2, it is deduced that the temperature of spark has risen above 973 K. This suggests that such a heat source has a sufficient energy to cause instantly tempering soften near-surface of the cast iron.

On the other hand, in case of metastable retained austenite in matrix, strain induced martensitic transformation is well-known to occur due to external stress from collision under impact-wear environment. It has already reported that the higher the volume of transformed martensite (hereinafter referred to as M), the better the wear resistance. In this study, volume fraction of martensite at initial state and it on the most worn surface after impact-wear test were measured with a ferrite scope. From the obtained results, M volume which is estimated from the transformation of metastable retained austenite was calculated. Figure 10 shows the relationship between increment of M volume in both 1223 K AsQ and 1423 K AsQ samples and impact angle. As can be seen in the figure, M volume in 1223 K AsQ samples is about 2.5% regardless of impact angle. Comparing the value of M in two types of samples at the same angle, it is found that 1423 K AsQ sample is at least 3.5 times larger than 1223 K AsQ one. Also, it seems that a slightly smaller peak of M appears at 45° for 1423 K AsQ sample, but the reason for this is still unclear.

On the most worn surface of two types of samples, measurement of hardness along depth direction was performed under a load of 2.94 N (0.3 kgf). Hardness profiles are shown in Fig. 11. Each measured value in the figure is the average hardness of a mixture consisting of matrix and primary carbides. From the figure, it is confirmed that the surfaces of both samples are hardened by continuous collision of iron grit during the impact wear test at any impact angle. Noted here that the maximum hardness near the surface which is related to surface hardening differs between 1223 K AsQ samples and 1423 K AsQ ones. As compared at a position of 30 µm below the worn surface, hardness of 1423 K AsQ samples reaches 1000 to 1100 HV, but that of 1223 K AsQ samples is lower, about 820 to 850 HV. Hardness of both samples gradually decreases with the depth direction. Above 1000 µm from surface, hardness of both samples hardly changes. Therefore, it is deduced that the occurrence of work hardening does limit to the region beneath impacted surface is below 500 µm in depth direction at any impact angle in this study.

Next, we focus our attention on matrix to clarify how the hardening amount of matrix onto surface changes with respect to impact angle. Hardness of the mixture of martensite and austenite in matrix containing secondary carbides was measured under a load of 9.8 N (0.1 kgf). The obtained result is shown in Fig. 12. Triangle marks and circle marks shown in the figure are 1223 K AsQ and 1423 K AsQ samples, respectively. Hardness of matrix without the influence of work hardening is indicated by solid marks, whereas hardness of matrix in regions of 30–50 µm far from the surface in which the contribution of work hardening is relatively large is indicated by open marks. Comparing hardness of the regions, it is observed that there is little change in hardening amount for 1223 K AsQ sample under various impact angles, but that of 1423 K AsQ sample tends to increase with impact angle. In addition, as compared hardness of two types of samples, amount of surface hardening in 1423 K AsQ sample exhibits much higher than that in 1223 K AsQ sample.

From the above results, it is found that microstructure near surface is sensitively affected by impact of iron grit. However, role of metastable austenite in wear behavior is considered to be contrary to that of martensite. The contribution of these phases to the wear resistance of high Cr cast iron and its wear behavior could be estimated as follows. When iron grit collides with objective sample, besides carbides are fractured, surface matrix is deformed plastically, resulting in formation of local dents. At that time, the generation of M from metastable retained austenite...
causes hardening of surface so the deformation due to the next collision of grit is suppressed. On the other hand, as mentioned above, when melts of iron grit adhere to the sample surface, initial martensite existing onto surface plays a role in causing self-tempering softening. Hence, the next collision of iron grit to the softened surface brings in plastic deformation on the surface. The difference in surface roughness between 1223 K AsQ and 1423 K AsQ samples shown in Fig. 6 could be explained by such repeated collision. For 1223 K AsQ samples, retained austenite volume is small and M transformation is difficult to occur on the entire surface of sample, so the increase of surface hardness is small. Furthermore, when initial martensite volume increases, softening of surface due to self-tempering easily occurs, so the degree of plastic deformation increases. As a result, many ripple patterns appear on the surface after impact of iron grit.

It has not been known yet the reason why weight loss is maximum at an impact angle of 45° when the volume of retained austenite increases, whereas it reaches the maximum at an impact angle of 60° as martensite becomes more stable. Bitter has reported that wear of surface (W) is a combination of deformation wear (WD) and cutting wear (WC) \( W = WD + WC \) when particles impact on the surface of objective sample.\(^1\) WD and WC are inversely proportional to the specific energy of deformation wear \( \varepsilon \) and the specific energy of cutting wear \( \varphi \), respectively. Specific energy is defined as the energy expended to remove 1 mm\(^3\) of material. According to Clark et al., the specific energies of \( \varepsilon \) and \( \varphi \) depend on the interaction between the objective samples and solid particles.\(^5\) They measured specific energies of \( \varepsilon \) and \( \varphi \) with respect to the wear behavior of various objective samples eroded by SiC particles in diesel oil. Brittle materials such as glass and alumina have been reported to have low \( \varepsilon \) and high \( \varphi \) values. The values of \( \varepsilon \) and \( \varphi \) of polymers are approximately equal low. By contrast, ductile metals are characterized that the values of \( \varepsilon \) and \( \varphi \) are both high. In this study, it is unclear how M transformation and softening tempering affect the change in specific energy of experimental cast iron, so further investigation of these parameters is required.

5. Conclusions

In this study, role of matrix structure in 27\% Cr cast iron quenched at 1223 K and 1423 K on impact-wear resistance was investigated. The results obtained are summarized as follows.

(1) The impact wear resistance of 27\% Cr cast iron strongly depends on matrix structure, which is changed by quenching temperature. By quenching at 1423 K, an increase of retained austenite volume results in the
improvement of impact-wear resistance. In contrast, when quenching is performed at 1223 K, initial martensite becomes a considerably stable phase and the impact-wear resistance deteriorates drastically.

(2) The relationship between weight loss and impact angle varies with the volume of retained austenite and initial martensite in matrix. Quenching at 1423 K results in a maximum impact-wear rate at 45°. In contrast, in the case of quenching at 1223 K, the wear rate reaches a maximum at 60°.

(3) Under impact-wear environment, strain induced martensitic transformation of metastable austenite and self-softening tempering of initial occur at the same time. Both phenomena give the different effects on surface hardening. When the volume of metastable austenite increases, hardening due to strain induced martensitic transformation overlaps with softening due to tempering of initial martensite, resulting in the suppression of wear rate.

REFERENCES