Evaluation of Impact Strength and Microstructure as Quality Criteria for Selected Materials

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Abstract

The article presents the results of analysis of the chemical composition, hardness, microstructure and toughness of selected structural materials. The focus is on the results of impact tests carried out on the 40H steel quenched and tempered at three different temperatures, on grey cast iron used in industrial practice (cast material for brake drums) and on ADI, all of them being considered representatives of the group of materials commonly used in the production of structural elements and finished products, including items for use in the automotive industry. The impact tests were performed at a reduced temperature (-20°C), at room temperature (20°C) and at elevated temperature (150°C), comparing the results obtained with the microstructure of materials tested. It has been shown that in the case of steel, the smallest changes in microstructure cause changes in toughness, while the effect of tempering temperature is in this case of secondary importance. It was also proved that under the conditions of ambient temperature and reduced temperature, better results were obtained for ADI. At elevated temperature, better results were obtained for grey iron castings.

Keywords: Steel, Cast iron, Hardness, Microstructure, Impact strength

1. Introduction

The main issue that requires careful consideration in both the development of a manufacturing technology and design of the finished products is the need to maintain the highest possible level of quality. This will be testified by the functional characteristics typical of a given material and a given design. It should be noted that although there are different types of service loads, the most common division is into two main types of loads, i.e. the static and dynamic loads acting at different temperatures and in different environments, both of which are widely discussed in the technical literature [1, 2, 3]. At the same time it is often emphasised that one of the basic properties that should be subjected to careful analysis is the impact strength of materials [4-9]. Like many other functional characteristics, this property is strongly related to both the manufacturing technology, leading to the controlled formation of the microstructure of material [4, 5, 7-9], and to the temperature at which impact tests are carried out [6, 7, 9]. This is important since many structures to be considered safe must operate in a failure-free mode at ambient, reduced and elevated temperatures. In this particular case it was decided to analyse the effect of temperature on the impact strength achievable in three totally different materials, i.e. a typical structural steel, grey cast iron with lamellar graphite used in industrial practice and ADI. The fatigue characteristics of all these materials were examined in detail in previous studies [10, 11, 12].
2. Test material

Tests and studies were carried out on 40H structural steel, which was subjected to quenching and tempering at different temperatures, cast iron with lamellar graphite commonly used in industrial practice for brake drums and ADI as a material very attractive because of its beneficial functional properties.

3. Chemical composition, hardness and microstructure of the examined materials

The chemical composition of the 40H structural steel selected for testing is given in Table 1. To determine how the heat treatment can change the resistance of this steel to impact loading, three variants of the heat treatment were applied (Table 2).

Table 1. Chemical composition of the examined steel.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>40H</td>
<td>0.44</td>
<td>0.66</td>
<td>0.25</td>
<td>0.012</td>
</tr>
</tbody>
</table>

S Cr Ni Cu
0.017 0.92 0.09 0.22

The estimated values of the uncertainty of measurements:
C, Si, Cr, Cu – 0.01 %; Mn – 0.02 %; P, S – 0.003 %; Ni – 0.005 %

Table 2. Parameters of the heat treatment (40H steel).

<table>
<thead>
<tr>
<th>Heat treatment</th>
<th>Heat treatment type identified in the sample designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching (in oil)</td>
<td>850°C  850°C  850°C</td>
</tr>
<tr>
<td>Tempering (2 h)</td>
<td>400°C  500°C  650°C</td>
</tr>
</tbody>
</table>

The results of hardness measurements after the heat treatment are given in Table 3.

Table 3. The results of hardness measurements-HRC.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>Heat treatment</th>
<th>Measurement results HRC</th>
<th>Mean hardness HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>45.5; 45.8; 44.1; 46.8; 46.3</td>
<td>45.7±1,1</td>
</tr>
<tr>
<td>40H</td>
<td>2</td>
<td>35.2; 34.9; 31.9; 31.6; 33.5; 39.2; 39.2</td>
<td>35.1±1,1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>26.0; 27.1; 21.7; 22.0; 26.0; 20.6; 22.0</td>
<td>23.6±1,1</td>
</tr>
</tbody>
</table>

The results show that the highest hardness values were obtained for steel subjected to the lowest tempering temperature (400°C – Table 2); the lowest values were obtained for steel subjected to the highest temperature of the tempering treatment (650°C – Table 2). The obtained results are consistent with the microstructure of the investigated steel shown in Figure 1.

Fig. 1. Microstructure of the investigated 40H steel grade, etched, conventional light, 500x: a) heat treatment variant – 1, b) heat treatment variant – 2, c) heat treatment variant – 3.

As a result of the metallographic examinations carried out on the 40H steel after etching it was found that, regardless of the heat treatment parameters used (Table 2), a sorbitic microstructure was obtained with well preserved needle-shaped martensite, characterised by only slight differences as regards the dispersion of the two structural constituents of sorbite (a mixture of cementite and ferrite) – Figure 1. The finest microstructure was
obtained at the highest tempering temperature (Fig. 1c) which, at the same time, yielded the lowest hardness values.

No soft skin defects were traced, and the trace impurities with non-metallic inclusions in the steel tested was below the reference standard No. 3 (according to PN-64/H-04510). The measured grain size corresponded to reference patterns 8–10 according to PN-84/H-04507.01.

The chemical composition of grey cast iron used for brake drums is given in Table 4, the results of hardness measurements are compared in Table 5, while microstructure is illustrated in Figure 2.

Table 4 Chemical composition of grey cast iron used for brake drums.

| Chemical composition of grey cast iron [wt%] |
|----|----|----|----|----|----|
| C  | Si  | Mn | Ni  | Mg | Cu |
| ±0.1 | ±0.1 | ±0.005 | ±0.005 | ±0.005 | ±0.02 |

Table 5. The results of hardness measurements taken on grey cast iron used for brake drums.

<table>
<thead>
<tr>
<th>Material</th>
<th>Measure technique</th>
<th>The results of hardness measurements</th>
<th>Mean hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>grey cast iron</td>
<td>HBW 2.5/187.5</td>
<td>168; 165; 162; 169; 166</td>
<td>166±6</td>
</tr>
</tbody>
</table>

The obtained results of hardness measurements are typical for the microstructure of grey cast iron, which is shown in Figure 2 and is composed of a pearlite of different dispersion with evenly distributed precipitates of flake graphite.

The chemical composition of ADI is given in Table 6, the results of hardness measurements in Table 7, while microstructure is illustrated in Figure 3.

Table 6. Chemical composition of ADI

| Chemical composition as examined on ADI samples [wt%] |
|----|----|----|----|----|----|
| C   | Si  | Mn | Ni  | Mg | Cu |
| 3.1–3.3 | 2.7–3.0 | 0.12 | 1.2–1.5 | 0.1 | 0.65–0.75 |
| ±0.1 | ±0.1 | ±0.005 | ±0.005 | ±0.005 | ±0.02 |

Table 7. The results of hardness measurements

<table>
<thead>
<tr>
<th>Material</th>
<th>Measure technique</th>
<th>The results of hardness measurements</th>
<th>Mean hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADI</td>
<td>HRC 46,08; 46,57; 47,31; 47,45; 46,32</td>
<td>46,75±0,41</td>
<td></td>
</tr>
</tbody>
</table>

The results of ADI hardness measurements compared in Table 7 and its microstructure (Fig. 3) confirm the correct choice of the heat treatment regime, which has produced a microstructure typical of this material, i.e. composed of the needles of ferrite, residual austenite, martensitic areas and carbide precipitates.

Fig. 2. Microstructure of grey cast iron, conventional light: a) unetched, 100x, b) etched, 500x.

Fig. 3. Microstructure of ADI, conventional light: a) unetched, 100x, b) etched, 500x.
3. Impact tests

The examined materials were subjected to impact tests using standard Charpy specimens according to PN-EN 10045-1:1994 with a length of 55 mm and a thickness of 10 mm (for steel) and 7.5 mm (for cast iron), with a U-shaped notch (in the case of steel) and a V-shaped notch (for cast iron), for which the height above the notch was 8 mm. Impact tests were carried out by Charpy technique according to PN-EN 10045 1:1994, using in studies a vertical INSTRON pendulum with Dynatup® 9250HV drop tower, operating within the energy range from 4.6 to 945.0 J, equipped with:

- force transducer model 8496-01 with a maximum load of 88,964 kN,
- speed sensor with an accuracy of indication ± 0.25% of the actual reading,
- load cell with an accuracy of ± 2% of the actual loading,
- position transducer – optical encoder with a resolution of 0.002 mm or ±0.05% of the value indicated and a repeatability of position ±0.015%.
- "Impulse" data archiving system with the frequency of saving the measured and control quantities of 1.17 MHz in the range of 7 ms (the bandwidth of 500 kHz),
- temperature chamber type LN2.
- Impact tests were performed at the following temperatures:
  1 – room temperature 20 ± 2°C (sample number I);
  2 – reduced temperature -20 ± 2°C (sample number II);
  3 – elevated temperature 150 ± 2°C (sample number III).

4. The results of impact tests

Several results of impact tests are presented in the form of graphs illustrating the courses of fracture work and load applied versus the sample deflection for 40H steel and ADI (Figs. 4 and 5), respectively.

![Graph showing the work of fracture and loading](image)

Fig. 4. Curves showing the work of fracture [▬] and loading [▬] for specimens nos. 2.1.1–2.1.3 made from 40H steel at a temperature of +20°C (tempering temperature – 500°C).

At the same time, graphs are presented to show how much steel differs from cast iron under the conditions leading to brittle fracture (impact).

![Graph showing impact test results](image)

Fig. 5. Curves showing the work of fracture [▬] and loading [▬] for specimens nos. 1.1–1.3 made from ADI at a temperature of +20°C.

During impacts, the volume of energy consumed and loads carried (impact forces) until fracture (total failure) are in the case of tempered 40H steel grade much higher than in the case of high-quality ADI. It should also be noted that before total failure, the 40H steel grade after the toughening treatment undergoes the elastic deformation, first, and plastic deformation, next, several times higher than the high quality ADI.

Moreover, from the presented graphs it follows that fracture of the 40H steel samples consumes much more energy than the energy needed in the case of ADI, which corresponds to the subsequent graphs (Figs. 6 and 7), showing the impact strength of 40H steel (Fig. 6), of grey cast iron used in industrial practice for brake drums and ADI (Fig. 7).

![Graph showing impact test results](image)

Fig. 6. Mean values of the impact strength KCU2 [J/cm²] obtained during Charpy impact test at different temperatures (from -20 to +150°C) on samples of 40H steel quenched in oil (850°C) and tempered at different temperatures (sample no. I – 400°C, sample no. II – 500°C, sample no. III – 650°C).

Based on the results of impact studies carried out at three different temperatures, i.e. reduced temperature (-20°C), room temperature (20°C) and elevated temperature (150°C), on 40H steel subjected to three variants of the heat treatment consisting of quenching (850°C) and tempering at three different temperatures...
(450°C, 500°C and 600°C), it was found that the highest values of toughness [J/cm²] were obtained for the third variant of heat treatment, i.e. for the highest temperature of tempering.

In this case, the impact test temperature was of minor importance and, regardless of the temperature at which the impact tests were carried out, i.e. reduced temperature (-20°C), room temperature (20°C) and elevated temperature (150°C), no significant differences have been found.

At the same time, the best results yielded the tests carried out at elevated temperature, which is consistent with the fact that at the reduced and ambient temperature, the materials are more brittle than at elevated temperature. Considering this fact, a better result of the impact strength obtained at elevated temperature is not surprising.

A comparative study of the results of impact tests carried out on grey cast iron used for brake drums and on ADI under conditions similar as in the case of 40H steel, i.e. at three temperatures: reduced temperature (-20°C), room temperature (20°C) and elevated temperature (150°C), has indicated the occurrence of the same effect for both cast iron grades. This effect is illustrated graphically in Figure 7, which shows that higher toughness values were obtained for both cast iron grades tested at elevated temperature.

![Impact strength vs. temperature](image)

**Fig. 7.** Mean values of the impact strength [J/cm²] obtained during Charpy impact test at different temperatures (from -20°C to +150°C) on samples of grey cast iron and ADI

This draws attention to the fact that in the case of reduced temperature and ambient temperature, better results were obtained for ADI, while at elevated temperature the grey cast iron had an advantage (Fig. 7). The obtained results are justified by the fact that ADI as a very hard material characterised by high strength values and absence of a plastic matrix will show a lower impact strength.

### 5. Conclusions

Based on the results of conducted studies it can be concluded that:

- even in the case of a homogeneous microstructure, which differs only slightly in the degree of the dispersion of the individual constituents, as is the case of the examined 40H steel, a significant influence of the tempering temperature has been observed, since the highest numerical values of the impact strength were obtained for the highest tempering temperature. These values, for all the test temperatures, were nearly three times higher when compared with the results obtained for the lowest tempering temperature,

- a slight difference has been observed in the 40H steel toughness determined at low, ambient and elevated temperature for the tempering temperatures of 400°C and 500°C, the best result being obtained in the impact test carried out at ambient temperature (20°C); for the highest tempering temperature (650°C), the highest impact strength was obtained in the impact test carried out at a reduced temperature (-20°C),

- in the case of 40H steel, the decisive factor influencing its impact strength is the type of heat treatment, in this particular case, it is the tempering temperature; the temperature of the impact test is of minor importance,

- in the case of ADI, better results were obtained for impact tests carried out at ambient and reduced temperature,

- in the case of grey cast iron, better results were obtained for impact tests carried out at elevated temperature.

The conducted studies have also proved that impact strength and microstructure can be regarded as quality assessment criteria for the examined materials, since microstructure shaped by the heat treatment parameters confers to the examined material the required impact strength, which represents an important parameter that should be kept in mind when the design- and material-related engineering solutions are developed.

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### References


