IMPACT RESPONSE OF Mo PREALLOYED SINTERED STEELS DETERMINED BY INSTRUMENTED TESTING

H. Danninger, G. Gelbmann, G. Straffelini

Abstract
The impact behaviour is one of the inherent weaknesses of sintered steels but on the other hand also a very sensitive indicator for the quality of interparticle bonding. In the present work, unnotched impact bars based on prealloy steel powder Fe-1.5% Mo were prepared, carbon content, compacting pressure, and sintering temperature being varied. In part, heat treatment by austenitizing, quenching and tempering was applied. Charpy impact testing using an instrumented pendulum hammer showed that there is a clearly positive correlation between dynamic maximum stress and yield stress on one hand and the displacement on the other hand for the effect of density and sintering intensity but a negative correlation for the effect of heat treatment, in the latter case higher density and/or sintering intensity rather increasing the stress values while in the as-sintered state the displacement grows. The carbon content has a significant effect in case of the sintered materials but hardly for the heat treated ones. Tempering in part changes the shape of the load-displacement curves, at least at high temperatures, but without too much effect on the integral impact energy.

Keywords: sintered steel, impact testing, instrumented tester, density, heat treatment

INTRODUCTION
Sintered steels as used in powder metallurgy precision parts differ from their wrought counterparts by the inherent porosity [1], which is mostly an evenly distributed network of “primary” porosity originating from the green compact, occasionally porosity is generated during the sintering process through transient liquid phase [2]. The porosity is the reason why the mechanical properties of sintered steels are usually inferior to those of wrought steels with similar composition and microstructure, the decrease of properties with higher porosity being usually more pronounced than the volume fraction of the pores [3, 4].

The effect of the porosity differs considerably between the individual mechanical properties [5,6]. Tensile and yield strength are moderately affected and exhibit an almost linear relationship to the density [4,7] while fatigue endurance strength and elongation are markedly more affected. That single mechanical property that is most sensitive to the porosity is the impact energy (IE); typically this property remains low at high to moderate porosity levels and strongly increases only at porosity levels < 6% [7]. It is generally acknowledged that this low impact resistance is one of the most pronounced weaknesses of pressed and sintered PM parts compared to wrought counterparts [5-8].

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This low impact energy results from the special microstructure of sintered steels: at least at $P_{\text{tot}} > 6\%$, i.e. in the porosity range of most industrially manufactured PM parts, the porosity is not isolated (forming a “swiss cheese” structure) but interconnected, like in a sponge, as can be shown by fractographic studies [9] and, if interconnected porosity is regarded roughly equivalent to open one, by He pycnometry [10]. This interconnected porosity means isolated sintering contacts, which in the case of mechanical loading results in localization of the plastic deformation at the sintering contacts [11] and thus in low deformed volume. Since the macroscopic ductility depends on the deformed volume [12], this means that although the sintered steels may behave highly ductile microscopically, they are macroscopically brittle. Increasing the cross section of the necks and especially joining the individual necks through transition from interconnected to isolated porosity brings about considerable improvement of the impact energy [7,13].

These positive changes of the microstructure are attained primarily by increasing the density – by raising the compacting pressure, by warm compaction [8] or high velocity compaction [14] or, to the extreme, by powder forging [15] – and by sintering at higher temperature and/or for longer times. The effect of the manufacturing parameters on the Charpy impact energy of sintered iron and steels has been studied frequently [7,16,17], also as a consequence of the fact that the impact fracture energy is the most sensitive mechanical property regarding interparticle strength, in that respect being significantly more meaningful for sintered steels than for wrought ones. However, most of the work has been limited to measuring the impact energy by itself – i.e. the integral value - while the determination of load-displacement graphs, through instrumented Charpy testing, so far has been rather rare (e.g. [18,19,20], systematically being performed only in very few laboratories. In [19] it has been shown that the notch effect plays a decisive role also for sintered steels, the unnotched specimens – which are standard for testing of sintered steels, see [21] – resulting in the highest impact energy values while with decreasing notch radius the IE drops drastically. This indicates that the reported insensitivity of sintered steels to external notches – derived from the hypothesis that the pores act as internal ones – should not be overestimated, at least not for impact loading.

In the present study, the mechanical behaviour of sintered steels has been investigated through instrumented Charpy testing. Low Mo alloyed steel prepared from prealloy powder has been used as model material, and the carbon levels as well as density and sintering intensity were varied accordingly, and also the effect of quench-and-temper treatments was studied.

**EXPERIMENTAL PROCEDURE**

The starting powders used were prealloyed steel powder Astaloy Mo (Fe-1.5%Mo, Höganäs) and natural graphite UF4 (Kropfmühl), the carbon levels being set at 0.3 and 0.7 mass% (nominal = admixed). 0.5% EBS (Microwax C) was added as lubricant. The powders were dry mixed for 1 h in a tumbling mixer and then compacted in a tool with floating die to form standard Charpy impact test bars (ISO 5754) of 55 x 10 x approx. 10 mm, the pressure being varied between 150 and 600 MPa, to result in an accordingly wide range of density levels. From both carbon variant, some specimens were double pressed at 800 + 800 MPa, then sintered and fully densified by HIP, in order to obtain pore-free reference materials. The bars were then dewaxed and sintered for 60 min isothermal soaking time in an SiC rod heated pusher furnace with gas-tight superalloy retort, the atmosphere being high purity nitrogen (99.999%) with a flow rate of about 2 l·min$^{-1}$. The sintering temperature ranged from 1120 to 1270°C. Part of the specimens were heat treated by austenitizing for 30 min at 890°C in high purity nitrogen, oil quenching, and tempering.
for 60 min at 400°C for the first test series and for the same time at various temperatures for the second one.

Characterization of the specimens included green and sintered density, from which data the porosity was calculated. For the sintered specimens it was assumed that C was present as cementite and Mo was contained in Fe-Mo solid solution (for which Vegard’s law is well fulfilled [22]). Furthermore, dimensional change during sintering and Vickers hardness (in cross sections) were measured, and metallographic investigations were done following standard routines for sintered steels, including impregnation of the pores. For etching, Nital (MeOH-3%HNO₃) was used. The instrumented Charpy testing was done on a 300 J Wolpert impact tester, load-displacement curves being recorded (in part the HIPed specimens did not break but were bent and pulled through the supports). Unnotched specimens were used, and the data given are mean values of 5 parallel tests each. The fracture surfaces were investigated in a scanning electron microscope Jeol 6400.

RESULTS AND DISCUSSION

Microstructures

The test series with varying density levels was produced as described above; heat treating was performed by oil quenching from 890°C and tempering uniformly at 400°C. The microstructures are shown in Figs.1-3. In the as-polished state, the main features are the pores; the effect of the compacting pressure on total porosity can be seen to advantage from Fig.1. It is also evident that the pores seem to be largely interconnected in Fig.1a but isolated in Fig.1b; however this is misleading as it is well established that up to density levels of at least 7.3 g·cm⁻³ the porosity is virtually fully open and interconnected, as can be proved by He pycnometry [10].

![Microstructures of sintered steels Fe-1.5%Mo-0.7%C, differently compacted, sintered 60 min at 1200°C in N₂; as polished (unetched).](image)

Fig.1. Microstructures of sintered steels Fe-1.5%Mo-0.7%C, differently compacted, sintered 60 min at 1200°C in N₂; as polished (unetched).
Fig. 2. Microstructures of sintered steels Fe-1.5%Mo-x%C, as sintered / HIP / heat treated (oil quenched and tempered 60 min at 400°C), respectively.
Fig. 3. Microstructures of sintered steels Fe-1.5%Mo-0.x%C, compacted at 600 MPa, sintered 60 min at 1200°C, quenched from 890°C and tempered for 60 min at varying temperatures.
The matrix microstructure were uniformly upper bainite after sintering (with occasional ferrite in the case of the lower carbon content) and fine in part tempered martensite in the heat treated state, as shown in Figs.2 and 3. As can be seen, the microstructures after sintering and after HIP are not too different, indicating that the cooling rates for both processes are fairly similar; not surprisingly that of the HIPed specimens is somewhat coarser, indicating slower cooling. Nevertheless, the microstructural types are roughly equivalent, and thus also the mechanical behaviour can be expected to be rather similar. In general, the coarser microstructure of the lower carbon material is evident, which holds not only for the as-sintered but also for the quenched and tempered specimens (compare Figs.2c, 2f).

The effect of the tempering conditions is fairly similar for both carbon levels, as evident from Fig.3. In the as-quenched state, the needle-shaped martensitic structure can be seen to advantage, at the higher carbon level also some retained austenite being present. With higher tempering temperatures the martensite gets progressively finer; while in the as-quenched material the coarser structure is found with higher carbon content after tempering the opposite is recorded, although in both cases the differences are not too pronounced.

Effect of the Density/Porosity

In Table 1, the properties of the test bars are given as a function of the compacting pressure. The relationship compacting pressure – density/porosity - hardness stands out quite clearly, as does the very pronounced effect of these parameters on the impact energy. The carbon content exerts a rather small effect on the impact energy; in the case of the quenched and tempered materials there is hardly any difference between 0.3% and 0.7% C. Regarding the hardness, the effect of the carbon level is more pronounced, especially after heat treatment; i.e. here it showed that while the effect of density/porosity is rather the same for all properties and materials, hardness and impact energy react differently to varying carbon levels.

Tab.1. Properties of sintered steel bars AstaloyMo-C, differently compacted, sintered 60 min 1200°C. In part heat treated (890°C -> oil + 1 h 400°C).

| AstaloyMo - 0.3% C |  |
|---|---|---|---|---|---|---|---|
| p<sub>c</sub> [MPa] | GD [g·cm<sup>-3</sup>] | SD [g·cm<sup>-3</sup>] | P<sub>tot</sub> [%] | Dim. change [%] lin. | HV30 (sintered) | HV30 (Q+T) | IE (AS) [J·cm<sup>-2</sup>] | IE (Q+T) [J·cm<sup>-2</sup>] |
| 150 | 5.34 | 5.42 | 31.2 | -0.32 | 58 | 93 | n.d. | 1.4 ± 0.2 |
| 250 | 5.95 | 6.02 | 23.5 | -0.27 | 74 | 126 | 3.5 | 3.2 ± 0.1 |
| 300 | 6.21 | 6.26 | 20.4 | -0.26 | 89 | 149 | 4.8 | 4.1 ± 0.2 |
| 400 | 6.53 | 6.60 | 16.1 | -0.24 | 114 | 191 | 7.2 | 5.9 ± 0.3 |
| 600 | 7.03 | 7.05 | 10.5 | -0.13 | 142 | 244 | 16.3 | 10.5 ± 0.5 |
| HIP | - | 7.87 | << | - | 224 | 454 | > 300* | > 300* |

* specimens did not break

| AstaloyMo - 0.7% C |  |
|---|---|---|---|---|---|---|---|
| p<sub>c</sub> [MPa] | GD [g·cm<sup>-3</sup>] | SD [g·cm<sup>-3</sup>] | P<sub>tot</sub> [%] | Dim. change [%] lin. | HV30 (sintered) | HV30 (Q+T) | IE (AS) [J·cm<sup>-2</sup>] | IE (Q+T) [J·cm<sup>-2</sup>] |
| 150 | 5.30 | 5.38 | 31.7 | -0.29 | 56 | 109 | n.d. | 1.4 ± 0.2 |
| 250 | 5.93 | 6.00 | 23.7 | -0.24 | 88 | 169 | 3.3 | 3.0 ± 0.2 |
| 300 | 6.21 | 6.26 | 20.4 | -0.19 | 114 | 190 | 4.6 | 4.0 ± 0.2 |
| 400 | 6.50 | 6.55 | 16.8 | -0.18 | 123 | 255 | 6.6 | 5.5 ± 0.4 |
| 600 | 6.96 | 6.97 | 11.4 | -0.10 | 165 | 315 | 12.6 | 9.6 ± 0.7 |
| HIP | - | 7.86 | << | - | 297 | 579 | 80.1 ± 13.1 | 44.8 ± 1.7 |
Figure 4 depicts typical load-displacement curves, obtained at the instrumented impact test, of the steel with 0.3% C for different porosity levels. As common for instrumented impact graphs, marked oscillations are recorded, the graphs being more difficult to interpret than e.g. those of tensile tests. Nevertheless, the different shapes, in particular the transition from elastic to plastic deformation, are well discernible.

It can be clearly seen that all the relevant parameters – yield load, maximum load, and maximum displacement – are positively correlated to the compacting pressure, i.e. the density. Furthermore it is evident that for the graphs obtained with the as-sintered materials (Fig.4a), not only total displacement is larger but the ranges of elastic and plastic deformation, respectively, can be rather clearly distinguished – although the former range is in part masked by oscillations – while after heat treatment plastic deformation is hardly noticeable (Fig.5a). This is still more evident from Fig.6 in which the load-displacement graphs for as-sintered and heat treated are shown side by side.

(a) Astaloy1.5Mo-0.3%C, as sintered

(b) Astaloy1.5Mo-0.7%C, as sintered

Fig.4. Load-displacement graphs at impact test for Astaloy1.5Mo-0.x%C, differently compacted, sintered 60 min at 1200°C in N₂.
For 0.7% C, quite similar results are obtained (Figs. 4b, 5b); here, also the loaddisplacement graphs for the HIPed, i.e. fully dense, specimens are shown. The enormous difference between a relative density of about 90% - as obtained at 600 MPa compacting pressure – and 100% (HIP) is clearly evident, both for the as-sintered and the heat treated materials. In fact the difference is still more pronounced since, as stated above, the HIPed specimens did not break but were bent, i.e. the energy consumed for actual breaking would be still higher.

![Graph](image1)

(a) Astaloy1.5Mo-0.3%C, heat treated

![Graph](image2)

(b) Astaloy1.5Mo-0.7%C, heat treated

Fig. 5. Load-displacement graphs at impact test for Astaloy1.5Mo-0.x%C, differently compacted, sintered 60 min at 1200°C in N₂, oil quenched from 890°C and tempered 60 min at 400°C.

As also indicated by the impact energy data, the effect of the carbon content is fairly small, in particular with regard to the maximum load, which can be attributed to the relatively similar microstructures. With regard to the maximum displacement, the scatter is larger, as can be seen when comparing the graphs for AstaloyMo-0.3% C compacted at 600 MPa given in Figs. 4a and 6, respectively; the very similar load but different maximum
displacement is evident. This can be taken as an indicator that at least for the as sintered materials, the pronounced scatter of the impact energy commonly observed in impact testing is largely due to variations in displacement rather than in maximum load. It is however evident also from Fig.6 that the differences between 0.3% and 0.7% C are small in the heat treated state; in this state, in general the lack of the plastic deformation range is visible.

![Fig.6. Load-displacement graphs at impact test for Astaloy1.5Mo-0.3%/0.7%C, differently compacted, sintered 60 min at 1200°C in N₂, in part oil quenched from 890°C and tempered 60 min at 400°C.](image)

The positive correlation between strength and ductility – which is not commonly found in wrought steel but which is a characteristic of sintered steels when changing the porosity level – can be seen to advantage when plotting e.g. the stress at maximum load (calculated following the equation for 3-point bending [23]) against the displacement at maximum load. This is shown for both carbon levels in Fig.7.

Here, in part an almost linear relationship is found, indicating that with increasing porosity, both load and displacement grow at approximately the same rate. This can be attributed to the strengthening of the sintering contacts which with increasing density level still remain isolated – interconnected sintering necks, i.e. isolated porosity, is found only at density levels >7.3 g·cm⁻³ but can absorb more energy due to their larger load-bearing cross section. Only at high density levels, i.e. in case of 600 MPa compacting pressure, the graph levels off for the as sintered state, indicating that here displacement grows more than load, as indicated by the respective graph in Fig.6.

When comparing the graphs for the as sintered and the heat treated state, the higher strength and lower displacement is evident, which is not surprising and agrees well with the known effect of heat treatment. However, it can also be seen that improving the as sintered materials, e.g. by raising the density, tends to preferentially result in higher displacement while for the heat treated steel, predominantly the stress levels are increased.
Fig. 7. Stress vs. displacement at maximum load for impact test. Astaloy1.5Mo-0.3/0.7%C, varying compacting pressure from 150 to 600 MPa, sintered 60 min at 1200°C. In part oil quenched from 890°C and tempered at 400°C.

Effect of the Sintering Temperature

For the standard compacting pressure of 600 MPa, specimens were sintered at different temperatures, the isothermal sintering time being held constant at 60 min. The properties are listed in Table 2; instrumented impact graphs are shown in Figs. 8 and 9 for as-sintered and heat treated materials, respectively.

Tab. 2. Properties of sintered steel bars AstaloyMo-C, compacted at 600 MPa, sintered 60 min at different temperatures. In part heat treated (890°C -> oil quenched + 1 h 400°C).

<table>
<thead>
<tr>
<th>C content [mass %]</th>
<th>Ts [°C]</th>
<th>Sintered density [g·cm⁻³]</th>
<th>HV30 (sintered)</th>
<th>HV30 (Q+T)</th>
<th>IE (sintered) [J·cm⁻²]</th>
<th>IE (Q+T) [J·cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1120</td>
<td>7.01</td>
<td>140</td>
<td>242</td>
<td>12.4 ± 0.5</td>
<td>9.0 ± 0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>1200</td>
<td>7.05</td>
<td>142</td>
<td>244</td>
<td>16.3 ± 2.1</td>
<td>10.0 ± 0.5</td>
</tr>
<tr>
<td>0.3</td>
<td>1270</td>
<td>7.09</td>
<td>162</td>
<td>286</td>
<td>21.7 ± 2.6</td>
<td>12.8 ± 0.9</td>
</tr>
<tr>
<td>0.7</td>
<td>1120</td>
<td>6.95</td>
<td>161</td>
<td>300</td>
<td>11.0 ± 0.5</td>
<td>8.1 ± 0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>1200</td>
<td>6.97</td>
<td>165</td>
<td>315</td>
<td>12.6 ± 0.6</td>
<td>9.6 ± 0.7</td>
</tr>
<tr>
<td>0.7</td>
<td>1270</td>
<td>7.04</td>
<td>180</td>
<td>347</td>
<td>18.2 ± 0.6</td>
<td>12.7 ± 0.9</td>
</tr>
</tbody>
</table>

The load-displacement graphs follow the pattern observed already in the previous chapter, i.e. a marked plastic zone in the as sintered state and predominantly elastic one after heat treatment. In both states, however, it is evident that the graph is extended to higher displacement, in part, though less pronounced, also to higher loads, and that the increase from 1120°C to 1200°C is markedly smaller than that between 1200°C and 1270°C sintering temperature. This overproportional effect of high temperature sintering is more pronounced for the higher carbon content.
Fig. 8. Load-displacement graphs at impact test for Astaloy1.5Mo-0.3%C, as-sintered

(a) Astaloy1.5Mo-0.7%C, as-sintered

These findings are in good agreement with other studies done with Mo alloy sintered steels. It has been shown [24] that the gigacycle fatigue endurance strength follows a similar but still more pronounced pattern: when increasing the sintering temperature from 1120 to 1200°C the gain in endurance strength is relatively small while from 1200 to 1280°C the endurance strength is almost doubled. For the practical viewpoint this means that, both for fatigue loaded and impact loaded sintered steel parts, higher sintering temperature is generally beneficial, but the full effect can only be exploited if the temperature is increased really significantly.
Fig. 9. Load-displacement graphs at impact test for Astaloy 1.5Mo-0.x%C, compacted at 600 MPa, sintered 60 min at different temperatures in N\textsubscript{2}, oil quenched from 890°C and tempered 60 min at 400°C.

In Figure 10, once more the stress at maximum load is plotted versus the respective displacement, this time for various sintering temperatures. As with the previous test series at varying density, the different graphs for as sintered and heat treated materials can be seen, and once more the graph for the as sintered materials indicates that the positive effect of higher sintering temperature (as well as of higher density) is noticeable mainly on the displacement while for the as sintered material mainly the level of maximum stress is affected.
Fig.10. Stress vs. displacement at maximum load for impact test. Astaloy1.5Mo-0.3/0.7%C, compacted at 300/600 MPa, sintered 60 min at different temperatures. In part oil quenched from 890°C and tempered at 400°C.

**Heat Treatment: Effect of Tempering Conditions**

Specimens compacted at 300 and 600 MPa, respectively, and sintered for 60 min at 1200°C were heat treated by oil quenching from 890°C and 60 min tempering at varying temperatures. The bars were then impact tested using the instrumented hammer. The results for the impact energy are listed in Table 3. (Since this test series was done using a separate batch of specimens, the results obtained in part slightly differ from those shown in the previous tables for nominally the same materials). Here it showed – somewhat surprisingly - that the impact energy did not depend significantly on the tempering temperature, at least for 0.3% C; for 0.7% C the impact energy was slightly lower as-quenched and stress-relieved at 100°C, respectively, but remained virtually constant after tempering between 200 and 700°C.

Tab.3. Mechanical properties of sintered test bars Astaloy1.5Mo-C, compacted 300/600 MPa, sintered 60 min at 1200°C in N$_2$, austenitized at 890°C, oil quenched, and 60 min tempered at varying temperatures.

**Hardness HV30**

<table>
<thead>
<tr>
<th>C(%)</th>
<th>p$_1$(MPa)</th>
<th>HV as-quenched</th>
<th>100°C</th>
<th>200°C</th>
<th>300°C</th>
<th>400°C</th>
<th>500°C</th>
<th>600°C</th>
<th>700°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>300</td>
<td>185</td>
<td>191</td>
<td>202</td>
<td>174</td>
<td>169</td>
<td>159</td>
<td>161</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>297</td>
<td>315</td>
<td>296</td>
<td>279</td>
<td>275</td>
<td>244</td>
<td>259</td>
<td>162</td>
</tr>
<tr>
<td>0.7</td>
<td>300</td>
<td>318</td>
<td>392</td>
<td>286</td>
<td>217</td>
<td>218</td>
<td>198</td>
<td>198</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>600</td>
<td>562</td>
<td>559</td>
<td>437</td>
<td>371</td>
<td>349</td>
<td>335</td>
<td>322</td>
<td>183</td>
</tr>
</tbody>
</table>

**Charpy impact energy [J·cm$^{-2}$]**

<table>
<thead>
<tr>
<th>C(%)</th>
<th>p$_1$(MPa)</th>
<th>IE as-quenched</th>
<th>100°C</th>
<th>200°C</th>
<th>300°C</th>
<th>400°C</th>
<th>500°C</th>
<th>600°C</th>
<th>700°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>300</td>
<td>4.9±0.8</td>
<td>4.9±0.2</td>
<td>4.4±0.4</td>
<td>4.0±0.3</td>
<td>4.4±0.3</td>
<td>4.7±0.6</td>
<td>4.5±0.3</td>
<td>4.5±0.8</td>
</tr>
<tr>
<td>0.3</td>
<td>600</td>
<td>12.8±1.4</td>
<td>12.2±1.3</td>
<td>12.5±0.9</td>
<td>10.7±0.8</td>
<td>11.0±0.6</td>
<td>12.6±0.9</td>
<td>12.6±0.9</td>
<td>13.0±2.3</td>
</tr>
<tr>
<td>0.7</td>
<td>300</td>
<td>3.1±0.5</td>
<td>3.4±0.6</td>
<td>4.8±0.3</td>
<td>4.6±0.3</td>
<td>4.7±0.4</td>
<td>4.7±0.4</td>
<td>4.7±0.1</td>
<td>5.0±0.3</td>
</tr>
<tr>
<td>0.7</td>
<td>600</td>
<td>7.8±1.3</td>
<td>6.2±0.7</td>
<td>13.4±0.4</td>
<td>11.8±0.5</td>
<td>10.8±0.6</td>
<td>12.4±0.3</td>
<td>12.3±1.0</td>
<td>12.3±1.1</td>
</tr>
</tbody>
</table>
The different load-displacement graphs are shown in Figs.11 and 12; in order to avoid overloading of the illustrations, the graphs for each composition have been divided into 2 figures. It can be seen that in fact the shape of the graphs does not vary markedly as a function of the tempering conditions. There is some rounding of the graphs – indicating at least some plasticity – esp. at T > 300°C; however the only quite pronounced change occurs after tempering at 700°C when the maximum load drops markedly while the total displacement increases. However, the area below the graphs – which corresponds to the consumed energy, i.e. the IE value – remains roughly the same. This effect is observed both for 0.3% C and, slightly less conspicuously, also for 0.7% C.

Fig.11. Load-displacement graphs at impact test for Astaloy1.5Mo-0.3%C, compacted at 600 MPa, sintered 60 min at 1200°C in N₂, oil quenched from 890°C and differently tempered for 60 min.
Fig. 12. Load-displacement graphs at impact test for Astaloy 1.5Mo-0.7% C, compacted at 600 MPa, sintered 60 min at 1200°C in N₂, oil quenched from 890°C and differently tempered for 60 min.

The results shown thus indicate that the impact energy by itself is surely a significant property esp. for sintered steels; however the same impact energy may result from high strength / low ductility or the other way round. Therefore, instrumented impact testing gives significantly more insight into the behaviour of sintered steels at high strain rate loading than does the less sophisticated variant commonly employed today.

**Fractography**

In Figures 13 and 14 typical fracture surfaces are shown. The lower area fraction of sintered contacts - i.e. lower load bearing cross section – in the specimens compacted at lower pressures is evident (Fig.13a, 13b); as stated previously, it is really surprising that the low-density sintered steels have any mechanical strength at all.
Fig. 13. Fracture surfaces of Astaloy 1.5Mo-0.3%C, differently compacted, sintered 60 min in N$_2$, in part oil quenched from 890°C and tempered 60 min at 400°C.

(a) AstMo-0.3%C, 150 MPa, 1200°C, heat treated
(b) AstMo-0.3%C, 400 MPa, 1200°C, heat treated
(c) AstMo-0.7C, 600 MPa, 1120°C, as sintered
(d) AstMo-0.7C, 600 MPa, 1270°C, as sintered

Fig. 14. Fracture surfaces of Astaloy 1.5Mo-0.7%C, compacted at 600 MPa, sintered 60 min at 1200°C in N$_2$, oil quenched from 890°C and differently tempered for 60 min.

(a) as quenched
(b) tempered 200°C
(c) tempered 400°C
(d) tempered 700°C
In the as sintered state, the influence of the sintering temperature is hardly noticeable in the 0.3% C specimens; at higher carbon level there is an increased fraction of cleavage fracture when sintered at higher temperatures; as found previously this is an indicator for improved interparticle bonding (Fig.13c, 13d).

When comparing the heat treated specimens to the as-sintered ones, on one hand the complete lack of transgranular cleavage in the former is evident, as has been shown for Mo alloy steels already in [25]. On the other hand, the moderate effect of tempering on the appearance of the fracture surfaces (Fig.14a-d) is striking, only the as quenched material being somewhat different; this is in good agreement with the similar impact energy values recorded with these materials for tempering between 200 and 700°C.

CONCLUSIONS

Instrumented Charpy impact testing of Mo alloyed sintered steels with varying carbon level and density showed that both for 0.3% and 0.7% carbon the increase of the Charpy impact energy with increasing density is linked to a virtually parallel increase of load and displacement at the maximum load level; the same hold for increasing the sintering temperature. This is apparently due to the presence of sintering contacts with larger cross section and the resulting higher deformed volume in the case of impact loading. When comparing as sintered and quenched and tempered materials it is evident that in the former case, higher density and more intense sintering has more effect on the displacement than on the stress while after heat treatment the opposite is observed.

Changing the properties of the matrix material by quenching and tempering at varying temperatures, in contrast, did not result in pronounced variation of the impact energy values despite different hardness levels, which is in good agreement with the very similar shapes of the load-displacement graphs obtained. Only in the case of tempering at 700°C markedly lower load and higher displacement was observed although the “integral” impact energy value was largely unaffected, and the appearance of the fracture surface was hardly different. This indicates that compared to other tests such as the standard impact testing procedure, the instrumented Charpy test can afford significantly more information about the behaviour of sintered steels under high strain rate loading.

REFERENCES

[21] Standard ISO 5754