FATIGUE AND MECHANICAL PROPERTIES OF THIN WALL SEMI-PRODUCTS PRODUCED BY INCREMENTAL FORMING PROCESSES

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Abstract
The flow forming process is one of the very progressive and flexible forming technologies. This technology is used to achieve the desired final shapes by making incremental deformations. The initial semi product is reduced to the required dimensions by the combined application of rollers and a mandrel. Stepped semi products for hollow shafts were produced by using this flexible technology. The research first assessed the influence of process parameters on the mechanical properties of the product. Mechanical properties were determined on mini tensile test specimens. Light microscopy was used to analyse the microstructure and the depth of penetration of the deformation into the wall of the semi product and the surface quality of the carbonized layer after the final thermo-chemical treatment of the product. The technological process was optimized on the basis of test results and its parameters were established. As the aim of this research was to achieve the best combination of technological and mechanical properties and also good fatigue properties, it was possible to use these results to define the practical application range of these products. At the end of experiment the fatigue properties were measured on the whole product and the Wöhler curve was established.

1. INTRODUCTION
The stepped hollow products were produced using flow forming. This progressive technology uses incremental deformations to achieve the required aims. This technology uses three rollers for the reduction to the final diameters. These three rollers are not driven and their rotation is attained through the friction between the wrought rotating semi-product and the shaping rollers (Fig. 1).

The investigated products were made with help of free fixed mandrel. Thanks of it the products with the long axial axis were produced without buckling in the longitudinal axis.

The experiment was focused on the examination of the influence of the forming process on the structural and mechanical properties of the final product.
2. THE INITIAL STATE OF SEMIPRODUCT

The material of the initial thin walled semi-product used in the experiment was 16MnCrS5 steel. It is low alloyed manganese-chromic steel with good hardening capacity for cementation (Table 1).

It is primarily used for medium stressed motor vehicle components. The initial diameter of the semi-product was 60 mm and wall thickness 6 mm. The material in the base state had a ferrite – pearlite structure with lamellar form and partial-spheroidal cementite. An average grain size was of about 10±5 µm (Fig. 2).

The combinations of a convenient type of cementite, mechanical properties with ultimate strength 508 MPa (Table. 2) and the micro-hardness of 172 HV0.2 provided sufficient structural formability for the experiment.

3. EXPERIMENT

The forming experiment was carried out on the machine developed for incremental forming processes. The forming was done at room temperature with a feed speed of 2 mm/rev and with intensive cooling of the forming product. The thin walled semi-products were formed from the turned initial surface size Ø 60 mm to Ø 45 mm and then to Ø 40 mm (Fig. 3).

For the purpose of metallographic analysis the products were cut into several parts and the influence of size reduction on the microstructure was observed in the whole cross-section of the thin wall product. Using light microscopy it was possible to observe the distribution of the deformation in the formed structure.

The ferrite-pearlite structure observed in the part reduced to Ø 45 mm was strongly deformed in the direction of the rollers’ rotation, especially in the ferrite area (Fig. 4).

As the distance from the surface increased, the size of the deformation decreased. In the middle of the product wall the structure was only gently deformed (Fig. 5).

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**Tab. 1.** Chemical composition of 16MnCrS5 steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>0.16</td>
<td>0.4</td>
<td>1.2</td>
<td>1.0</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Fig. 2.** The ferrite-pearlite structure with spheroidal and lamellar form of cementite

**Tab. 2.** The mechanical properties of the material in the initial state

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>$R_m$ [MPa]</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$A_{5mm}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 60</td>
<td>508</td>
<td>350</td>
<td>41</td>
</tr>
</tbody>
</table>

**Fig. 3.** The shape of final product after the flow forming

The ferrite-pearlite structure observed in the part reduced to Ø 45 mm was strongly deformed in the direction of the rollers’ rotation, especially in the ferrite area (Fig. 4).

As the distance from the surface increased, the size of the deformation decreased. In the middle of the product wall the structure was only gently deformed (Fig. 5).
The highest deformation in the whole volume of the product was achieved in the area where the semi-product is reduced to the smallest diameter of 40 mm. Particularly in the under-surface zone (Fig. 6) the structure showed marked deformation and the orientation of the deformed grains was almost parallel to the product surface. The pearlite area in the part reduced to 40 mm diameter underwent higher deformation in comparison with the part reduced to 45 mm. But even the reduction to 40 mm did not result in a homogeneous deformation distribution in the whole wall size of the product and the middle part of the product was again less deformed in comparison with the surface.

For the examination of mechanical properties of the whole product the mini-tensile tests were carried out on each part of the product. The reason for the choice of mini-tensile test was caused insufficient material volume for the conventional tests.

The results showed that $R_m$ increased by about 150 MPa in the area of Ø 45 mm or by 170 MPa in area of Ø 40 mm. The increase of $R_{p0.2}$ was higher than 300 MPa in both formed parts. The residual ductility $A_{5\text{mm}}$ was higher than 20% (Table 3) and (Fig 7).

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>$R_m$ [MPa]</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$A_{5\text{mm}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 45</td>
<td>657</td>
<td>655</td>
<td>26</td>
</tr>
<tr>
<td>Ø 40</td>
<td>683</td>
<td>680</td>
<td>24</td>
</tr>
</tbody>
</table>

Fig. 4. The structure after reduction to Ø 40 mm in the distance 0.25 mm from the surface

Fig. 5. The structure after reduction to Ø 45 mm in the distance 0.25 mm from the surface

Fig. 6. Structure after reduction to Ø 45 mm in the middle of the wall
3.1 THE HEAT TREATMENT

16MnCrS5 is commonly used in the cemented state. For this reason, the hollow stepped products were subsequently carburized.

This heat treatment consists of preheating to 910°C with a 140 min hold at this temperature with carbon concentration 1.1%. Then the concentration of carbon is reduced to 0.8% and the hold time is 45 min. After that, the carburizing temperature is decreased to 860°C.

For the next evaluation of the carburization process it was necessary to determine the carburized depth. The micro-hardness profile was measured from the outer surface to the middle section of the wall with 0.05 mm steps, with load 20 g. The results of micro-hardness measurements show that the carburized depth reached about 0.8 mm (Fig. 10). The maximal load size was in the distance 0.1 from the surface and it was 735 HV0.2. From this value the size of micro-hardness was falling with rising distance from the surface under the 500...
The mechanical properties of the final thermo-chemical treated products were established by mini-tensile testing and the specimens for these tests were cut off from the middle part of the product. The resulting average value of the ultimate strength was 1300 MPa. The yield strength was around 1200 MPa and the ductility $A_{5\text{mm}}$ was 19% (Tab. 3).

### 3.2 THE FATIGUE TESTS

The final product can be potentially used as the cyclic loaded components. From that reason it is important to know the fatigue properties of the product in the time.

The fatigue tests were carried out on the products in the initial state and also on the products with carbonized layer. The fatigue tests were performed according to norm ČSN 420363 and the fatigue specimens were loaded with alternating plane bending load on the machine O-50 (Fig. 11). The size of load was measured using a strain gauge on the outer surface in the chosen position of the whole product.

The measured size of stress was compared with the calculated value of the stress (Fig. 12). From broken tested specimens it was established that the fatigue cracks were in the area with the highest stress level. This area was in the transition from Ø 40 mm to Ø 45 mm.

In the case of the carburized product, the fatigue crack initiated on the outer surface and on some tested specimens inclusions were observed in the cracks.

In the case of the product without heat treatment the fatigue crack initiated on the defects on the inner surface. These defects were observed in the formed part as well as in the unformed part of the product (Fig. 10). The origin of this defect seems to be in the semi-product production. The defects did not influence carburised specimens in this respect, as all fatigue cracks were initiated on the free outer surface. The probable reason is in the retarding effect of the pressure strain in the carburized products.

The fatigue limit of the carburized products at a stress level of 530 MPa was established on the basis of the fatigue test. The estimated fatigue limit of the uncarburized products was about 230 MPa (Fig. 14).

<table>
<thead>
<tr>
<th>$R_m$ [MPa]</th>
<th>$R_{p02}$ [MPa]</th>
<th>$A_{5\text{mm}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>1204</td>
<td>19</td>
</tr>
</tbody>
</table>

**Fig. 9.** The resonance fatigue machine

**Fig. 10.** Profile of hardness in carburized layer

**Fig. 12.** The stress distribution in the product
4. CONCLUSION

The long stepped semi products were successfully prepared using the flow forming process. On the basis of metallographic analysis the deformation distribution in the wahl was established. The deformed structure was especially in the surface layer. As the distance from the surface increased, the intensity of the structure deformation fell. Each part of the final product was measured using mini-tensile tests. The products were consequently thermo-chemical treated and then metallographically and mechanically evaluated. The fatigue limit was established at 530 MPa on the heat treated product. The estimated fatigue limit of uncarburized products was about 230 MPa. The fatigue cracks initiated in the case of the carburized product on the outer surface. The initiation of the fatigue cracks occurred on the inner surface when the uncarburized product was loaded. The reasons for the initiation of fatigue cracks on the inner surface were microscopic surface defects. The influence of the defects only on the uncarburized product is probably caused by the retarding effect of the pressure stress in the carburized surface.

ACKNOWLEDGEMENTS

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LITERATURE
