MINI-THIXOFORMING OF TOOL STEEL X210Cr12

Hedvika MIŠTEROVÁ, Andrea RONEŠOVÁ, Štěpán JENÍČEK
University of West Bohemia, Pilsen, Czech Republic, EU, daisman@vctt.zcu.cz

Abstract
Forming in the thixotropic state is one of the alternative forming methods, which allows producing semiproducts with relatively complicated shape. The process is based on semi-product forming in the region between solid and liquid, where the material exhibits the thixotropic behaviour. Among the advantages of this technology belongs the possibility to produce components with complicated shape in one step and to utilize lower forming forces. On the other hand, high forming temperatures and the narrow forming temperature interval can be considered as disadvantages.

A die was designed for this technology and practical testing was carried out using a range of forming strengths and temperatures. The shape of the hollow was varied to find out fluidity. Steel workpieces of various shapes several millimetres in size were created using this technology. The tool steel X210Cr12 was used for the development of an alternative forming process. The structures were observed using light and laser confocal microscopy.

Keywords: semi-solid state, thixoforming, X210Cr12

1. INTRODUCTION
The first experiments with forming metals in a semi-solid state date back to 1972. Alloys of tin and lead were used at temperatures between solid and liquid [1]. The resulting structures were so unusual that they immediately became the centre of attention for many research teams who started to investigate the hidden potential of this technique. Since then thixoforming is generally referred to as ‘semi solid metal forming’ (SSM). Thixoforming combines the advantages of casting and forming and allows the manufacture of complex shaped components [2].

The essence of the process is the formation of a semi-product which, after heating to melting temperature, is partially in a liquid form and partially in a solid form. The proportion of the melt is usually between 10 – 40% [2]. The semi-product then exhibits thixotropic behaviour, which means it has high viscosity which rapidly falls when subjected to shear stress. When left at rest, the material re-acquires its high viscosity which asymptotically resembles its original value [3]. This technology gives rise to very unusual structures even with conventional materials. For example, high-alloyed steels whose structure after working in a semi-solid state is composed predominantly of globular or spheroid polyhedral particles of metastable austenite enclosed in a lamellar network [4].

2. MINI-THIXOFORMING
A new as yet unpublished method for manufacturing small components in the semi-solid state is ‘mini-thixoforming’. Mini-thixoforming differs from conventional thixoforming in that it is necessary to develop new approaches for managing the temperature fields in the small volume of the material - this means a range of volumes up to one cubic centimetre. Minimum temperature deviations must be ensured throughout the heating process to obtain even distribution of temperature throughout the entire volume of the semi-product. Another advantage of mini-thixoforming is the very rapid solidification from the semi-liquid state after deformation. This means that unconventional structures can be obtained even with commonly used industrial
materials, which have an interesting combination of not only mechanical but physical properties. These are multi-phase structures which are a result of, among other things, uneven distribution of chemical elements in the liquid and solid phases.

3. EXPERIMENTAL PROGRAMME

The aim of the experimental programme was to describe the influence of die cavity parameters on the quality of product after mini-thixoforming and to find out the optimal cross section of input to the cavity for the best fluidity of semi-molten materials.

Metallographic sections through the resulting products were analysed using optical and scanning electron microscopes. Hardness was measured in multiple locations of the products. Volume fractions of microstructure components were identified using X-ray diffraction analysis in a diffractometer with Co-Kα source.

3.1. die for Mini-thixoforming

A titanium die was designed for the mini-thixoforming process (Fig. 1). The die was built into the thermomechanical simulator (Fig. 1). Titanium offers a good combination of ultimate strength, ductility and has a more favourable mass than steel. It also has excellent corrosion resistance in strongly oxidising conditions. A very important requirement is that the die should be non-magnetic, as heating is carried out using resistance-induction heating.

For ease of manipulation of the tool and semi-products, the die is composed of four parts which ensure problem-free disassembly of the die and it means there is no need for lubricant. A special principle for forming is lateral compression of the heated material into the forming cavity (Fig. 1).

The temperature of the semi-product is continually monitored using a thermocouple. The thermocouple is attached to the semi-product by a corundum tube which also prevents the metal from flowing into the channel during forming.

![Fig. 1: a) Titanium die for mini-thixoforming, b) Die built into the machine](image)

3.2. Properties of the used materials

X210Cr12 tool steel was selected for the experiment (Tab. 1). It has a wide temperature interval between the solid and liquid state which means that it is suitable for working in a semi-solid state. This material is also characterized by the fact that it is difficult to form and machine using conventional methods because its high
chromium content makes the material very hard and relatively brittle. The initial structure is formed of a ferrite matrix with globular cementite and primary chrome carbides (Fig. 2).

The liquid volume fraction in relation to the heating temperature was calculated in the JMatPro program. The suitable heating temperature was determined to fall into the temperature interval from 1290 to 1330°C. Heating within this temperature interval leads to obtaining 40-60% of the liquid phase in the material. According to computations the liquid phase formation begins at the temperature of about 1225°C. But from the previous experiment it was found that the right heating temperature is only 1265°C [5, 6, 7]. This difference between the calculated and real heating temperature was caused probably by the fast heating rate.

The semi-product for mini-thixoforming with a cylindrical dimension of 42 mm in length and 6 mm in diameter had blunt cone ends to allow clamping between copper electrodes.

Table 1: Chemical composition of X210Cr12 steel

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content [%]</td>
<td>2.01</td>
<td>11.3</td>
<td>0.27</td>
<td>0.23</td>
<td>0.08</td>
<td>0.014</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Fig. 2: Initial structure of X210Cr12 steel

3.3. Technological aspects of mini-thixoforming

The rapid solidification during thixoforming allows unconventional structures to be obtained even using conventional materials. From a technological point of view however, it is best that the material is kept at the highest possible temperature throughout the deformation process so as to achieve the required filling of the cavity. Due to the need of high temperature there is a risk of overheating the die resulting in slow cooling of the material. This means that it is essential to accelerate the whole thixoforming process to avoid this undesired effect.

A simple flat cavity (width 5 mm, length 15 mm and thickness 3 mm) was designed for the first experiment. The cavity served to determine the key forming parameters; speed of deformation and forming force. If the parameters are not confined to precise limits, either the cavity will be incompletely filled or it will be entirely empty. After the parameters for the cavity were optimized, the cavity was completely filled (Fig. 3a). The optimum forming temperature for this material was 1265°C, speed of deformation 1m/s and maximum force 7kN. The next step was to reduce the diameter of the cavity inlet opening and extend it. The width of the
cavity inlet was reduced to 1.5mm and extended to 20mm, whilst maintaining a cavity width of 5mm and the optimized forming parameters. The surface quality in the first two thirds is exceptional, but in the final third there are some imperfections in the filling (Fig. 3b) which, because they were not observed with the smaller cavity volume, are probably caused by the limited volume of the metal melt.

**Fig. 3:**

- **a)** Demonstrator with short, perfectly filled cavity
- **b)** Example of imperfectly filled flat cavity

After the experiments with straight cavities, variously shaped demonstrators were designed to test the ability of filling the cavity through a tapered inlet opening. The modular construction of the die not only allowed changes to the shape of the cavity but also the lining of the die and changes not only the shape but also the inlet opening. It was shown that, given enough volume of melted material, it is possible to perfectly fill the cavity (Fig 4). The cross section of the inlet opening was 5x3, 3x3, 3x1.5 mm and the forming parameters were kept from the simple flat cavity for the whole of the following experiment.

Further experiments were designed with a view to the miniaturization of the resulting product. The input with cross section 2.5 mm x 2 mm conically tapering to 1.5 mm x 2 mm was filled practically with no remaining unfilled space (Fig. 4), and further reduction to 0.8 mm x 5 mm resulted in only slight leakage up to 6 mm.

**Fig. 4:** Completely filled cavities with tapered inlet opening

### 4. Metallographic Analysis

After mini-thixoforming, because of the high heating temperature and very rapid cooling, the structure of the semi-product was formed of polyhedral grains of austenite bordered by a fine network formed of a mixture of ledeburitic carbides and austenite (Fig. 5). An x-ray diffraction phase analysis showed that the fraction of austenite in structure was 96 %. The mean size of austenite grains, 12 – 14 µm, is considerably smaller than that of conventionally thixoformed materials. The hardness of the microstructure reached 332 HV10. The micro-hardness measurement was used to estimate the hardness of individual components. It was found that the micro-hardness of austenite grains varies from 320 to 400 HV0.05 and approx. 550 HV0.05 for the carbide network.
The structure of the resulting semi-product was homogenous. Only near the contact surface with the die, a thin layer formed of fine dendrites developed due to the melt segregation and rapid solidification.

![Fig. 5: Structure of X210Cr12 steel after mini-thixoforming](image)

Chemical analysis using EDX was carried out on a scanning electron microscope (Fig. 6, Tab. 2). The aim was to describe the distribution of the alloying elements in the structural components. The results showed that the polyhedral austenitic grains contain less chromium compared to the ledeburitic-austenite network.

**Table 2:** Results of chemical composition [wt%]

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Si</th>
<th>Cr</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum 1</td>
<td>0.18</td>
<td>8.14</td>
<td>87.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Spectrum 2</td>
<td></td>
<td>8.60</td>
<td>86.97</td>
<td>0.20</td>
</tr>
<tr>
<td>Spectrum 3</td>
<td>0.22</td>
<td>8.36</td>
<td>86.81</td>
<td>0.29</td>
</tr>
<tr>
<td>Spectrum 4</td>
<td>0.18</td>
<td>22.82</td>
<td>59.79</td>
<td>0.01</td>
</tr>
<tr>
<td>Spectrum 5</td>
<td></td>
<td>22.92</td>
<td>64.27</td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>0.22</td>
<td>22.82</td>
<td>87.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Min.</td>
<td>0.18</td>
<td>22.92</td>
<td>59.79</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Fig. 6: Chemical analysis of the structure after mini-thixoforming](image)
5. CONCLUSIONS

The experiments showed that forming X210Cr12 steel in the semi-solid state can be used to manufacture even very small components of various shapes. Mini-thixoforming was carried out in a die cavity and the shapes of the resulting demonstrators varied. From the results it is clear that the ability of the material to fill the entire volume of the die cavity is excellent when there is enough metal melt and adequate inlet opening thickness provided. At thicknesses less than 1 mm the fluidity of the metal using this technology is significantly lower. Unconventional otherwise typical thixoforming microstructures were obtained as a result of the combination of rapid solidification and suitable chemical composition of steel. The microstructure was composed of polyhedral metastable austenitic grains surrounded by ledeburite network. Austenite fraction was over 95 % and the hardness reached 332 HV10.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) and the Czech Science Foundation (Grantové agentura České republiky, GAČR) through the joint, binational projects WA 2602/2-1 and GA ČR P107/11/J083.

REFERENCES