The article presents the study of surface's quality of punch stamp built from a Textit J composite, Fibroflex 5 polyurethane and X210Cr12 steel tool. The composite and polyurethane were used for rapid tooling, during which an experimental stamping of the die was verified. During the experiments, various machining strategies have been proposed and optimised using SolidCAM software with consideration of the maximum Scallop Height. Later, the results and conclusions of the unconventional materials' machining were applied during machining of the steel punch stamp. The surface's quality was reviewed by measuring surface roughness in selected areas of the punch stamp. The roughness parameters of $R_A$ and $R_z$, the profile curves and the Abbott-Firestone curves were compared.

Key words: punch stamp, roughness, profile trace, Abbott-Firestone curve

1. INTRODUCTION

Complex shapes of elements produced using a variety of molding technologies are obtained by a direct contact with the production’s machine tool through forging, drawing, casting or injection molding. Therefore, the die’s functional surfaces are also considered as complex shapes due to their direct impact on the final state of the product. The production process of the die is the key factor due to the high costs of its production.

The article compares the roughness of different materials, with the cut being performed under various conditions which were selected as optimal for each of the materials. The CNC machining of the punch stamp was performed during the experiments. The punch stamp was a component of a production die used for production of tin bodyparts for cars (Figure 1) by metal sheets’ forming. The first and the second punch were used for the purpose of verification of the process, particularly in determination of the parameters of the process and for a production of
a test serie. The testing punches were built from unconventional materials such as Textit J composite and Fibroflex 5 polyurethane. The final punch stamp was built from the X210Cr12 steel.

Textit J is a composite material which is reinforced with textile layers and a phenol-formaldehyde resin. As a material, it is well resistant to water and oils and is recommended by its producer for manufacturing of machine parts. Selected properties of the material are described in Table 1 [2]. Resistance to water and chemicals allowed for cooling with a cutting fluid as well as to use lubricants during the process of deep drawing of the car body. Material’s properties decide on its high manufacturability and the producer offers no restrictions for manufacturing.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific weight [g \cdot cm^{-3}]</td>
<td>1.3–1.4</td>
</tr>
<tr>
<td>Bending strength vertically to layers [MPa]</td>
<td>110</td>
</tr>
<tr>
<td>Impact strength [K \cdot J \cdot m^2]</td>
<td>7</td>
</tr>
<tr>
<td>Heat conductivity [W \cdot m^{-1} \cdot K^{-1}]</td>
<td>0.2</td>
</tr>
<tr>
<td>Coefficient of thermal linear dilatability [1 \cdot K^{-1} \cdot 10^{-6}]</td>
<td>20–40</td>
</tr>
<tr>
<td>Temperature resistance [°C]</td>
<td>120</td>
</tr>
</tbody>
</table>

The Fibroflex 5 polyurethane is intended to be used for functional parts of stamp dies and its selected properties are described in Table 2 [4]. The producer recommends the cutting speed for milling of \( v_c = 100 \text{ m} \cdot \text{min}^{-1} \).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shore-A Hardness</td>
<td>80</td>
</tr>
<tr>
<td>Density [g \cdot cm^{-3}]</td>
<td>1.07</td>
</tr>
<tr>
<td>Max. deformation [%]</td>
<td>35</td>
</tr>
<tr>
<td>Elongation to tear [%]</td>
<td>490</td>
</tr>
<tr>
<td>Tearing strength [N \cdot mm^{-2}]</td>
<td>34.4</td>
</tr>
<tr>
<td>Modulus of elasticity [N \cdot mm^{-2}]</td>
<td>38</td>
</tr>
<tr>
<td>Tensile strength [MPa]</td>
<td>34</td>
</tr>
</tbody>
</table>

Fibroflex 5 was used for production of an elastic punch. The most important parameters of the process of deep drawing with elastic punches are described in [1]. The principle and most common problems of application of elastic punches are
Surface roughness properties for punch stamps built...

presented in [13], with one of the parameters being the surface roughness of the elastic punch. Machining of polyurethane materials is described in [8] and it presents certain recommendations for the cutting edge’s maximum side rake and cutting depth, which are both directly related to polyurethane’s structure.

The ball end mill are commonly used for finishing of the surfaces shaped by milling. The final roughness of the surface is mostly influenced by the distance between the adjacent tool paths and the tool’s diameter. Several approaches to this problem are presented in [3].

Optimisation of the feed rate in milling of the complex-shaped surfaces, considering the surface roughness, is described in [5]. Critical values of surface roughness from the view of the finishing are determined in [7]. The influence of the tool’s shape and the parameters of milling on the surface roughness is determined in [11]. The evaluation and optimisation of strategies for roughing and finishing are described in [12]. The strategies for evaluation, focusing on the final quality of the surface and the cutting forces, are also presented in [6] and [9].

Due to the complex shape of the dies’ active surfaces, triaxial milling is often adequate for machining [10]. The final surface roughness is not uniform and depends on the actual position of the tool’s axis and the position of the machined surface [14].

2. EXPERIMENTAL WORKS

The CAD model of the car body shown in Figure 1 was used for the determination of the punch’s shape. Punches of two experimental dies (Figure 2) and the production die are identical in shape, therefore the same production process was performed. The machining was performed on a triaxial CNC Emco Mill 155 machine and it determined the selection of machining strategies.

Figure 1. The car body as a shell CAD model with major dimensions in mm

Figure 2. Detailed view of the punch (Textit J) of the experimental die
Some alternatives were proposed for punch machining. The one presented involves a sequence of four milling operations. Roughing using CONTURA strategy leaves the allowance of 0.4 mm on all surfaces. It is followed by finishing of the top punch surfaces by parallel lining strategy (Figure 3). The third stage is finishing of the punch stamp’s side walls using the constant Z strategy (Figure 4). The Scallop Height of 0.005 mm was set. The final fourth operation finishes the body of the punch stamp.

Figure 3. Tool paths and orientation for parallel lining strategy for finishing top surfaces
Figure 4. Tool paths and orientation for the constant z strategy for finishing side walls

Tool used for punch production from Textit J:
- roughing – the ZPS-FN end mill, HSS Co8 material, diameter of Ø 10 mm, tooth No. z = 2, rake angle $\gamma_o = 12^\circ$, clearance angle unentered,
- finishing – the ZPS-FN ball end mill, HSS Co8 material, diameter of Ø 4 mm, tooth No. z = 2, rake angle $\gamma_o = 12^\circ$, clearance angle unentered.

In consideration of the specific material, the cutting conditions were determined by the cutting conditions for machining of the N material group. The cutting conditions were adjusted as follows:
- roughing: cutting speed $v_c = 106 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.06 \text{ mm}$,
- finishing: cutting speed $v_c = 62 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.02 \text{ mm}$.

Tool used for the production of the Fibroflex 5 polyurethane punch:
- roughing – the ZPS-FN end mill, HSS Co8 material, diameter of Ø 10 mm, tooth No. z = 2, rake angle $\gamma_o = 12^\circ$, clearance angle unentered,
- finishing – the ZPS-FN ball end mill, HSS Co8 material, diameter of Ø 8 mm, tooth No. z = 2, rake angle $\gamma_o = 12^\circ$, clearance angle unentered.

The cutting speed was increased gradually from the recommended value of 100 m · min$^{-1}$ to 150 m · min$^{-1}$ with no negative effects on the machined surface. The cutting depth was varied from 0.25 mm to 2.25 mm with a step of 0.25 mm, also with no negative effects on the machined surface. The feed rate per tooth was altered from the value of 0.008 mm to 0.017 mm. It was confirmed that the increasing feed rate decreases the final quality of the surface. The sur-
face quality also rapidly decreased during milling with cooling, therefore no cooling was applied. Based on the experiments for Fibroflex 5 stamp punch, the cutting conditions were set up as follows:

- roughing: cutting speed $v_c = 150 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.015 \text{ mm}$,
- finishing: cutting speed $v_c = 120 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.018 \text{ mm}$ to $0.025 \text{ mm}$ – the lower value was used for the milling of the top punch surfaces, the higher value was used for the milling of the punch side walls.

The produced punch stamp was built from the X210Cr12 steel. The conclusions from the previous Textit J and Fibroflex 5 experiments were applied. The production process and the machining strategies were approved and adopted with all the variations. The tools used were the same as for the machining of the Textit J punch. The cutting conditions were changed according to the tool’s producer’s recommendations for the steel, and set as follows:

- roughing: cutting speed $v_c = 80 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.09 \text{ mm}$,
- finishing: cutting speed $v_c = 40 \text{ m} \cdot \text{min}^{-1}$, feed per tooth $f_z = 0.02 \text{ mm}$.

Machined punch stamps are presented in Figure 5.

![Figure 5. Comparison of punch stamps (from left to right) – Textit J, Fibroflex 5, steel and areas for roughness measurement](image)

The experimental analysis of the final surface roughness was performed using Surftest SJ-301Mitutoyo profilometer. The parameters for surface roughness measurement were chosen based on the STN EN ISO 4287 standard and set as follows:

- $\lambda_c$ profile filter – 0.8 mm,
- number of basic lengths $N = 5$,
- measured profile: $R$ (median line system),
- filter: Gauss,
- evaluated length $l_n = 4 \text{ mm}$.
3. Results and evaluation

Roughness parameter $Ra$ (arithmetical mean of the assessed profile) is the basic and the most commonly evaluated parameter to describe surface’s microgeometry. However, when two surfaces are evaluated by $Ra$ parameter, the same value of $Ra$ might ignore a different morphology of the surface. It is necessary to determine another roughness parameter to evaluate the surfaces in an accurate manner. Therefore, the $Rz$ parameter (maximum height of profile) was measured, as well as the profile curves and the Abbott-Firestone curve were determined. The roughness parameters were measured for five points located on the surface of the punch – three on the top surface, where the parallel lining strategy was used, and two on the side walls, which were machined using the constant $z$ strategy. Ten measurements of $Ra$ and $Rz$ values were taken from each of the points and their arithmetic means are presented.

Measured values of the arithmetic means are shown in the Figure 6. For all of the measured surfaces, the values of $Ra$ were within the range of 1.60 to 3.29 µm for Textit J; 4.27 to 11.29 µm for Fibroflex 5 and 1.55 to 5.46 µm for the steel.

![Figure 6. Comparison of the measured values’ arithmetic mean of $Ra$ for all materials](image)

Measured values of the maximum height of the profile ($Rz$) are shown in Figure 7. For all surfaces, the measured values of $Rz$ were in the range of 7.91 to 14.45 µm for Textit J; 21.43 to 49.35 µm for Fibroflex 5 and 8.11 to 23.85 µm for the steel.
Profiles of the top surfaces of the hood of the punch for each material are presented in Table 3. Table 4 presents profiles for the roof. Table 5 presents the Abbott-Firestone curves of top surfaces of the punch for each of the materials. These profiles were selected due to the biggest difference of roughness parameters shown in Figure 6 and Figure 7.

Based on the values of the surface roughness and profiles of the evaluated surfaces measured for each material, approximately the same character of the surfaces was observed, considering its morphology. They were proved to be oriented, with a certain periodicity of surface topography resulting from the technology offered by CNC machining. The periodicity is visibly clearer for the front and the rear hood than for the roof. With the material of the punch in consideration, the periodicity is clearer for the X210Cr12 steel than it is for the Textit J and Fibroflex 5.

The conclusion is also confirmed by the Abbott-Firestone curves for the front and the rear hood, comparing to the curve of the roof, mainly in the 40% level of the profile (thick line – see Table 5). The Abbott-Firestone curves for Textit J measured on the front and the rear hood reaches almost a double of the values of the Abbott-Firestone curve for the roof. These values are halfway lower for the X210Cr12 steel. Differences in the Abbott-Firestone curves are minimal for material Fibroflex 5.
Table 3

Comparison of the profiles measured on the front hood

<table>
<thead>
<tr>
<th>Material</th>
<th>Textile J</th>
<th>Fibroflex 5</th>
<th>X210Cr12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td><img src="image3" alt="Graph" /></td>
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<tr>
<td>Profile 2</td>
<td><img src="image4" alt="Graph" /></td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
</tbody>
</table>

Table 4

Comparison of the profiles measured on the roof

<table>
<thead>
<tr>
<th>Material</th>
<th>Textile J</th>
<th>Fibroflex 5</th>
<th>X210Cr12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
<td><img src="image9" alt="Graph" /></td>
</tr>
<tr>
<td>Profile 2</td>
<td><img src="image10" alt="Graph" /></td>
<td><img src="image11" alt="Graph" /></td>
<td><img src="image12" alt="Graph" /></td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

The aim of the study was to review the quality of complex shaped surfaces on the examined punch stamps. Based on the performed experiments, the measured values of surface roughness and the process of machining of unconventional materials, the following conclusions were gathered:

− Textit J material was approved for rapid tooling of functional parts of stamping dies, especially for experimental stamping dies and the optimisation of the process.

− Experience gained in machining of punch stamping of Textit J allowed to optimise the milling strategies and significantly influenced the quality of production of the punch stamp as well as of the drawing stage.

− Machining of Fibroflex 5 and testing of the cutting conditions allowed to machine functional parts of Fibroflex 5 stamping dies with the desired surface quality.

− Comparison of the measured values of surface roughness presented the difference in the values of $Ra$ and $Rz$ depending on the material, which result from the material’s properties and its machineability. Therefore, different cutting conditions have been applied and these influenced the final quality of the surface.

− The Scallop Height measured in CAM system overrode by $Rz$ roughness for all materials. This confirm the previous hypothesis that the final surface quality is influenced by a number of factors connected to machine-tool-part
production system. These factors are not included in the CAM systems for the time being.

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REFERENCES