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Influence of machining process on the mechanical behaviour of injection-moulded specimens of talc-filled Polypropylene

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Abstract

The mechanical properties of injection-moulded components are usually obtained by conducting uniaxial tensile tests on dog bone specimens. Current standards do not regulate the machining process used to make the coupons and do not quantify an acceptance limit of the surface roughness. The surface qualities of milling, laser cutting and water jet cutting were examined in this study for 18% talc-filled Polypropylene using optical measurements. It shows that the machining processes influence the surface roughness of the specimen, leading to different strengths at failure of the same thermoplastic material. The specimens machined by the water jet technology produced the roughest sample edges and exhibited the lowest resistance to failure in tensile tests. On the contrary, the milling process generated the best edge quality, which showed repeatable testing results.

Keywords: Surface Roughness, Failure Strain, Tensile Test Specimens, Water Jet Cutting, Laser Cutting, Milling

1. Introduction

The injection moulding process has been widely used in the automotive industry to manufacture thermoplastic components because it generates final products in one process. However, for the determination of the mechanical properties of thermoplastic materials, it is necessary to prepare specimens from injection-moulded plaques by cutting them into required geometries according to the testing standards for tensile, compression and shear tests.

When experimental tests are conducted on polymers, scientists usually refer to ISO 2818 (Plastics – Preparation of test specimens by machining) where the selection of methods to machine notched specimens is limited to milling and stamping. After this standard has been published in 1996, other machining technologies have been adopted in industrial workshops, such as laser and water jet cutting to reduce manufacturing time and costs. No scientific study has been conducted to understand if these new technologies influence the mechanical testing results.

Since a machining process removes part of the material and generates a new surface finish, the quality of the surface finish is usually checked for the compliance with engineering standards. For polymer materials, ISO 2818 prescribes that “the machined surface and edges of the finished specimens shall be free of visible flaws, scratches or other imperfections when view with a low-power magnifying glass (approximatively x5 magnification)”.[1] This statement leads to personal interpretations of the meaning of imperfections but it clearly remarks that in some cases the surface quality of the test specimens might influence the mechanical responses of the specimens made from the same material.

Few studies have been conducted to assess the influence of the surface quality on the mechanical behaviour of reinforced polymer materials. Persson et al. [2] and Tagliaferri et al. [3] examined the effect of the hole quality on the mechanical strength of specimens made from fibre-reinforced plastics.
It was observed that the machining defects led to a reduction of mechanical strength in quasi-static and fatigue tests. The influence of the surface roughness was also investigated by Eriksen [4] on thermoplastic materials, i.e. Polyoxyethylene (POM), Polypropylene (PP) and Styrene acrylonitrile (SAN), reinforced by short glass fibres. The Charpy impact, monotonic bending and fatigue bending strengths were observed to be independent of the surface roughness. These inconsistent observations showed that it is necessary to conduct further investigations to understand the influence of the surface quality of the specimen on its mechanical response in standard tests. Furthermore, it has been observed that additional treatments, such as coating and grounding of the specimen surface [5] and annealing [6] that modifies the crystalline structure of the polymer, influence the measured strength and toughness of polymers.

This study is aimed to understand the influence of different machining processes (milling, water jet and laser cutting) on the quasi-static uniaxial tensile properties of mineral filled Polypropylene by correlating the surface roughness with the experimental data from uniaxial tensile tests.

2. Methodology

2.1 Specimens Preparation

Dog-bone shaped samples were machined from Hostacom TKC451N (18% talc-filled Polypropylene copolymer) plaques according to ISO 527-2:2012 with the nominal dimensions in Figure 1. Tensile specimens were cut in the centre of 4 mm injection-moulded plates as prescribed in ISO 294-5:2013 in order to avoid edge and injection gate effects.

Three different manufacturing technologies were employed: milling, laser cutting and water jet cutting. The CNC milling machine produced a clean edge by using a double edge. The HPC Laser Script model LS1290 PRO 80 Watt was used at 71% power and 21 mm/s where the material was engraved three times before obtaining the final product. The cut tensile specimens exhibited a small heat-affected-zone due to the melting and solidification of the material during the cutting process. The residual powder was removed from the samples using methanol. The FLOW machine was adopted to cut the injection-moulded plates by high-pressure jet of water.

2.2 Surface Roughness Measurements

The quality of the lateral surface was initially assessed by a visual inspection of the samples and it was observed that no macro defects were produced by the three technologies. However, the milling machine generated the smoothest lateral edges. To characterise and quantify the surface topography obtained by different cutting processes, the 3D surface roughness parameters were evaluated at the side surfaces of the specimens (area of interest in Figure 1).

The experimental methodology proposed by Shivanna et al. [7] and Abouelatta [8] was adopted by implementing optical measurement devices and processing topographical images. As shown in Figure
2, the Keyence VHX-5000 electronic confocal microscope was used to acquire high resolution 3D images implementing a point-by-point acquisition method.

Three different images were taken on each side of the samples where the focused area on the surface was 1.5 mm (thickness direction) x 1.8 mm (flow direction). The captured images were converted into grayscale pictures and then imported to MATLAB where the coloured surface topography in Figure 3 was generated by scaling the brightness values at each pixel in a matrix form.

![Surface topography image acquisition using electronic confocal microscope.](image1)

![Image processing result of two-dimensional images into the 3D surface profile of the focused area used to evaluate 3D surface roughness parameters.](image2)
Once the peak and valley height function $Z = Z(x, y)$ was obtained by implementing the Abouelatta [8] algorithm in MATLAB, the 3D surface roughness parameters in Table 1 were evaluated from the three-dimensional expansion of 2D surface roughness parameters according to ISO 25178-2:2012.

<table>
<thead>
<tr>
<th>NAME</th>
<th>SYMBOL</th>
<th>DERIVATION</th>
<th>MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arithmetic Mean Height</td>
<td>$S_a$</td>
<td>$\frac{1}{A} \int_{A}</td>
<td>Z(x, y)</td>
</tr>
<tr>
<td>Root Mean Squared Height</td>
<td>$S_q$</td>
<td>$\frac{1}{A} \int_{A} Z(x, y)^2 , dx , dy$</td>
<td>Root mean square of the heights in the measured area $A$.</td>
</tr>
<tr>
<td>Skewness</td>
<td>$S_{sk}$</td>
<td>$\frac{1}{S_q^3} \left( \frac{1}{A} \int_{A} Z^3(x, y) , dx , dy \right)$</td>
<td>Degree of skew and symmetry of peaks and valleys about the average surface. It is strongly influenced by isolated peaks/valleys. - $S_{sk} = 0$: Symmetrical about the average plane. - $S_{sk} &gt; 0$: Skewed upward relative to the average plane. - $S_{sk} &lt; 0$: Skewed downward relative to the average plane.</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>$S_{ku}$</td>
<td>$\frac{1}{S_q^4} \left( \frac{1}{A} \int_{A} Z^4(x, y) , dx , dy \right)$</td>
<td>Yardstick for determining the sharpness of a surface and expression of the pointing of the height distribution. It is strongly influenced by isolated peaks/valleys. - $S_{ku} = 3$: Normal distribution. - $S_{ku} &gt; 3$: Height distribution is spiked. - $S_{ku} &lt; 3$: Form of the surface roughness height distribution is squashed.</td>
</tr>
<tr>
<td>Maximum Peak Height</td>
<td>$S_p$</td>
<td>$\max(Z(x, y))$</td>
<td>Largest peak height on the surface in the measured area.</td>
</tr>
<tr>
<td>Maximum Valley Depth</td>
<td>$S_v$</td>
<td>$</td>
<td>\min(Z(x, y))</td>
</tr>
<tr>
<td>Maximum Height</td>
<td>$S_z$</td>
<td>$S_p + S_v$</td>
<td>Sum of the maximum peak height and maximum valley depth in the measured area.</td>
</tr>
</tbody>
</table>

Table 1 3D surface roughness parameters

The skewness and kurtosis parameters were introduced to differentiate surface profiles that have the same arithmetic mean height but they are characterised by different shapes. To visually understand their meaning, Gadelmawla et al. [9] provided a graphical representation of the 2D parameters which is displayed in Figure 4. The skewness represents the symmetry of the profile about the mean surface and the kurtosis defines the sharpness of the probability density of the profile.
2.3 Uniaxial Tensile Tests

Uniaxial tensile specimens were conditioned and tested in the standard atmosphere 23/50 according to ISO 291:2008. A constant crosshead speed of 2 mm/min was applied by the Instron loading machine to obtain a nominal strain-rate of 0.002 1/s within the gauge length, in which uniaxial tensile stress state is assumed to occur during the test.

3. Experimental results and discussion

3.1 Surface Roughness

The surface roughness parameters of the specimen manufactured in the centre part of the injection moulded plaques were evaluated by averaging six measurements: three obtained from the left side and three from the right side of the same test piece. The edge roughness of the other samples of the same injection-moulded plaque is assumed to lie within the uncertainty of the measurement.

<table>
<thead>
<tr>
<th>Cut</th>
<th>Plaque</th>
<th>Sa [µm]</th>
<th>Sq [µm]</th>
<th>Ssk</th>
<th>Sku</th>
<th>Sp [µm]</th>
<th>Sv [µm]</th>
<th>Sz [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILLING</td>
<td>1</td>
<td>0.82</td>
<td>1.04</td>
<td>0.69</td>
<td>10.65</td>
<td>14.08</td>
<td>3.89</td>
<td>17.96</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.85</td>
<td>1.08</td>
<td>0.17</td>
<td>4.37</td>
<td>10.33</td>
<td>4.66</td>
<td>14.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.31</td>
<td>1.62</td>
<td>0.34</td>
<td>2.89</td>
<td>6.91</td>
<td>4.91</td>
<td>11.82</td>
</tr>
<tr>
<td></td>
<td>TOT</td>
<td>0.99±0.28</td>
<td>1.25±0.32</td>
<td>0.40±0.027</td>
<td>5.97±4.12</td>
<td>10.44±3.59</td>
<td>4.49±0.53</td>
<td>14.76±3.08</td>
</tr>
<tr>
<td>LASER</td>
<td>4</td>
<td>3.91</td>
<td>4.96</td>
<td>-0.29</td>
<td>3.51</td>
<td>17.84</td>
<td>23.56</td>
<td>41.40</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>5.33</td>
<td>6.53</td>
<td>0.12</td>
<td>2.65</td>
<td>21.09</td>
<td>20.76</td>
<td>41.85</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5.00</td>
<td>6.34</td>
<td>-0.16</td>
<td>3.93</td>
<td>24.08</td>
<td>32.10</td>
<td>56.17</td>
</tr>
<tr>
<td></td>
<td>TOT</td>
<td>4.75±0.75</td>
<td>5.94±0.85</td>
<td>-0.11±0.21</td>
<td>3.36±0.65</td>
<td>21.00±3.12</td>
<td>25.47±5.91</td>
<td>46.47±8.40</td>
</tr>
<tr>
<td>WATER JET</td>
<td>7</td>
<td>9.35</td>
<td>11.90</td>
<td>-0.16</td>
<td>3.87</td>
<td>66.75</td>
<td>55.06</td>
<td>121.82</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12.08</td>
<td>14.94</td>
<td>-0.02</td>
<td>3.55</td>
<td>73.97</td>
<td>63.14</td>
<td>137.11</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>12.41</td>
<td>15.63</td>
<td>0.09</td>
<td>5.10</td>
<td>99.92</td>
<td>57.35</td>
<td>157.27</td>
</tr>
<tr>
<td></td>
<td>TOT</td>
<td>11.28±1.68</td>
<td>14.16±1.99</td>
<td>-0.03±0.12</td>
<td>4.17±0.82</td>
<td>80.21±17.44</td>
<td>58.52±4.16</td>
<td>138.73±17.78</td>
</tr>
</tbody>
</table>

Table 2 Mean values of 3D surface parameters of dog bone shaped specimens machined by milling, laser and water jet cutting technologies.

Table 2 shows that different machining processes produced a variable surface quality of the final product characterised by the same material and same nominal dimensions. The height distribution was spiked for all the measured samples which was validated by the Kurtosis variable Sku that was greater than 3 for all the cutting technologies.

By analysing the arithmetic mean height Sa and the maximum height Sz, it was concluded that the CNC milling machine manufactured the components with the best edge quality and the water jet
technology generated tensile test samples with the roughest edges. In addition, all the tensile samples obtained by the milling cutting process exhibited that the distribution of peaks and valleys is skewed upward relative to the average plane. Differently, the samples machined with the laser or water jet cutters do not show a consistent Skewness Ssk sign for all the specimens but a symmetrical profile can be assumed.

3.2 Mechanical Response

The mechanical properties of mineral filled PP were investigated by testing nine specimens from three plaques for each cutting process. The qualitative mechanical properties of 27 test pieces were estimated by calculating the stresses and logarithmic strains from the measured force and cross-head displacement corrected from the machine compliance.

From experimental results in Figure 5-7, it was observed that the elasticity response of the material was consistent for the specimens machined with the same technology but the elastic modulus was slightly higher for the water jet as summarised in Table 3. Although yield was observed to initiate at the same state of stress, the failure strain depended evidently on the cutting process adopted. The milling machine produced the specimen with the highest strain to failure and with the lowest variability of the results. On the contrary, the water jet cutting generated the specimens with the lowest failure strain and highest uncertainties.

![Figure 5 Quasi-static uniaxial tensile tests of nine samples machined using milling cutting](image)
Figure 6 Quasi-static uniaxial tensile tests of nine samples machined using laser cutting

Figure 7 Quasi-static uniaxial tensile tests of nine samples machined using water jet cutting

<table>
<thead>
<tr>
<th>Machining</th>
<th>Elastic Modulus [MPa]</th>
<th>Yield Stress [MPa]</th>
<th>Failure at Strain [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MILLING</td>
<td>177.45±3.68%</td>
<td>17.78±1.03%</td>
<td>86.38±5.04%</td>
</tr>
<tr>
<td>LASER CUT</td>
<td>173.73±2.19%</td>
<td>17.04±0.74%</td>
<td>47.67±9.85%</td>
</tr>
<tr>
<td>WATER JET</td>
<td>197.98±1.30%</td>
<td>17.50±0.77%</td>
<td>32.48±20.64%</td>
</tr>
</tbody>
</table>

Table 3 Quasi-static tensile properties of mineral filled Polypropylene test pieces machined by different cutting processes

3.3 Influence of Surface Roughness on Failure Strain

Different machining processes produced testing coupons that did not exhibited the same failure strain under tensile loading. If the arithmetic mean height is used to quantify the surface roughness, it is possible to conclude from Figure 8 that the quality of the lateral surfaces of dog bone shaped samples influences the logarithmic strain at failure of mineral filled Polypropylene.

The machining process induced defects in the lateral surface of tensile specimens that caused the crack growth when the specimen was loaded. The higher the roughness of the lateral specimen surface, the higher the chance to initiate a macro crack in the specimen. Therefore, the failure of the
specimen is dependent on its surface roughness. In addition, larger variability of experimental results was observed for the water jet process which produced poor edge quality.

![Figure 8 Arithmetic Mean Height influence on failure resistance of injection-moulded specimens of talc-filled Polypropylene](image)

**4. Conclusions**

It is shown that the machining process influences the mechanical response of the mineral filled Polypropylene specimen; in particular, the surface roughness has considerable influence on the failure strain of the material.

The milling machining generated the tensile specimens with the best edge quality and repeatable experimental results. Therefore, for the calibration of material strength models, it is preferable to adopt this machining technology because it induces a low level of damage to the specimen surface. Surface defects may promote the formation and extension of macroscopic cracks.

For the preparation of other mechanical property tests (e.g. compression and shear tests), it is also important to reduce the surface roughness of the specimen to ensure that the influence of surface roughness on the testing results is within the acceptable limit.

**Acknowledgment**

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**Reference**


