End Milling of Elastomers—Fixture Design and Tool Effectiveness for Material Removal

This paper describes the machining of elastomers using sharp, woodworking tools and the machining of cryogenically cooled elastomers. Due to the lack of information on tool selection for elastomer machining, a set of thirteen tools that cover different sizes and tool geometries and materials was used in this study. Fixture design was found to be critical in machining of elastomers because of its relatively low elastic modulus. The cutting force created during machining can generate significant deformations in the elastomer workpiece. The finite element technique is used to analyze the structural stiffness of the elastomer workpiece under different geometric configurations. The effective stiffness is defined to quantify and compare the stiffness of elastomer workpiece machined by different tool sizes. The cleanliness of the groove machined by end milling is investigated. Use of some down-cut end-milling tools effectively removed the elastomer material at room temperature and generated a clean groove. The tool configuration and part fixtureing are identified as the two most important variables that affect the cleanliness of machined grooves. Cooling the elastomer workpiece by solid carbon dioxide (dry ice) to about $\pm 78.6^\circ$C improved the machined surface finish. [DOI: 10.1115/1.1616951]

1 Introduction

Elastomers, also known as rubbers, are the long-chain polymers that exhibit many unique material properties. According to ASTM D 1566-00 [1], rubber is a material that is capable of recovering from large deformations quickly and forcibly, and can be, or already is, modified to a state in which it is essentially insoluble (but can swell) in boiling solvent. Elastomer materials are a popular choice for shock and vibration absorption, sealing, flexible and stretchable uses, and electrical and thermal insulation. Table 1 illustrates the unique mechanical and thermal properties of elastomers, compared to other engineering materials. Elastomers have a very low elastic modulus and high percent of elongation before fracture, which makes the machining of elastomers a challenge. Elastomers also have very low thermal conductivity. Under cyclic loading, elastomers exhibit significant hysteresis, which contributes to their energy absorption capability.

Most elastomer parts are manufactured using the molding rather than machining process. In the molding process, raw polymeric materials are mixed with other additives and then heated, melted, and pressed into a mold. Inside the mold, the polymer material is subjected to a controlled temperature-pressure-time cycle. The material is cured, vulcanized, and cooled to produce the desired properties and geometry. To manufacture elastomer parts with complicated shapes, such as tire and footwear tread patterns, a set of molds must first be produced. Manufacturing these molds is expensive and time-consuming. For these reasons, machining offers an attractive alternative for manufacturing custom or prototype elastomer components. Potential applications of elastomer machining include prototype tire and footwear tread patterns, rubber-metallic seals, vibration dampers, and scrap tire recycling equipment.

In this study, two methods for effectively machining of elastomers are investigated. One approach is to use very sharp, down-cut woodworking router tools. The other is to cryogenically cool the elastomer with solid carbon dioxide (dry ice) to about $\pm 78.6^\circ$C before machining.

Very little research has been conducted on the machining of elastomers. The most notable elastomer machining research was conducted by Jin and Murakawa [5]. They used several carbide end mills of various sizes and helix angles to cut grooves on three types of elastomers, H-NBR, Norbornone rubber, and silicone rubber, at various speeds. Better surface finishes and lower forces were observed for machining at high speeds with high helix angle cutters.

Cryogenic machining of elastomers has also been investigated. At low temperatures, elastomers transform to a brittle, glassy phase, which makes the machining process more efficient. As shown in Table 1, elastomers have very low thermal conductivity (about 0.13–0.16 W/m·K). This is beneficial because the workpiece, after being cryogenically cooled, will remain at low temperature for an extended period of time. To recycle rubber tires into pellets for further processing, White [6] showed that grinding elastomers at cryogenic conditions helped reduce the pellet size and improve surface finish. McLeish [7] studied cryogenic grinding of flexible polyurethane foam. Using cryogenically cooled tools, Wang, et al. [8] and Wang and Rajurkar [9] demonstrated that the wear of liquid nitrogen cooled PCBN tools was reduced when machining silicon nitride, and Evans [10] studied liquid nitrogen cooled single point diamond turning of stainless steel. For a cryogenically cooled workpiece, Bhattacharyya et al. [11] studied the turning of Kevlar composites, Hocheng and Pan [12] researched the laser grooving of fiber-reinforced plastic, and Zhao and Hong [13] and Ding and Hong [14] investigated the machining of low carbon steel. Paul and Chattopadhyay [15,16] studied the grinding of hardened steel using a cryogenic coolant jet. Recently, Hong [17] investigated the economics and ecological impact of cryogenic machining and Dhar et al. [18] studied the role of cryogenic cooling on cutting temperature in steel turning.

In this paper, the end milling of elastomers is investigated. End milling experiments were performed with a wide range of milling tools for several speeds, feeds, and workpiece temperatures. The

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objective of these experiments was to better understand the basic machinability of elastomers and to identify end milling tools and conditions that produce clean and burr-free surfaces in elastomers.

2 Preliminary End-Milling Experiments

Due to the very low elastic modulus and large elongation to fracture of elastomers, machining of elastomers is different and, in some aspects, more difficult than machining of metals. To understand these difficulties, a preliminary milling test was conducted. For this test, a 4.76 mm diameter high-speed steel double-flute end mill was used to cut a groove in an elastomer tire segment with the spindle speed of 3600 rpm (53.8 m/min peripheral cutting speed), feed speed of 0.42 mm/s (3.5 μm/ flute feed), and depth of cut of 6.35 mm. Figure 1 shows the elastomeric workpiece with several machined grooves. As shown in this figure, the resulting machined surface is very rough with burr-type debris attached to the workpiece. It was found that the workpiece adjacent to the milled area deformed significantly due to the cutting forces. The up-cut end mill, as defined in Figs. 2(a) and 2(e), was used in this test. This up-cut end milling configuration is widely used in metal machining. When up-cut milling was used, the soft elastomer workpiece pulled away from its supporting base. The resulting machined surface was very rough due to the inadequate support for the workpiece.

![Fig. 1 Results of the preliminary elastomer end milling test that failed to make a clear-cut groove on an elastomer workpiece with steel cable reinforcement (a) side view and (b) front view](image)

Table 1 Comparison of the properties of elastomer and other materials [2–4].

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Ultimate stress to fracture (MPa)</th>
<th>% of elongation to fracture</th>
<th>Thermal conductivity (W/m K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastomers</td>
<td>0.0007–0.0004</td>
<td>0.47–0.5</td>
<td>7–20</td>
<td>100–800</td>
<td>0.13–0.16</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>70–79</td>
<td>0.33</td>
<td>100–550</td>
<td>1–45</td>
<td>177–237</td>
</tr>
<tr>
<td>Steel, high-strength</td>
<td>190–210</td>
<td>0.27–0.3</td>
<td>550–1200</td>
<td>5–25</td>
<td>35–60</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>100–120</td>
<td>0.33</td>
<td>900–1200</td>
<td>10</td>
<td>7–7.5</td>
</tr>
<tr>
<td>Plastic, Nylon</td>
<td>2.1–3.4</td>
<td>0.4</td>
<td>40–80</td>
<td>20–100</td>
<td>0.3</td>
</tr>
<tr>
<td>Plastic, Polyethylene</td>
<td>0.7–1.4</td>
<td>0.4</td>
<td>7–28</td>
<td>15–300</td>
<td>0.13–0.16</td>
</tr>
</tbody>
</table>

Based on preliminary experimental observations, good fixture design of the workpiece was found to be critical for machining smooth surfaces. The elastomer workpiece surrounding the machining area can deform significantly due to machining force. To counteract the deformation, it was found that the down-cut end milling, as illustrated in Figs. 2(a) and 2(d), worked more efficiently for elastomer machining. The down-cut end milling is commonly used in wood and plastic machining to reduce surface damage. During the down-cut end milling, chips are pushed into the work-surface and the workpiece is pushed against the fixture. This has provided a better support for the workpiece and alleviates some part fixturing problems. In contrast, up-cut end milling pulls the elastomer material away from the fixture. It is noted that this definition of up- and down-cut has been adopted from terminology used in woodworking tooling. Different definitions of up- and down-cut milling could be found in traditional end milling of metals [19,20]. Figures 2(c) and 2(f) also show the mixed-cut configuration, which could take advantage of both up- and down-cut in a more complicated tool.

3 Fixture Design

Based on preliminary milling tests, good fixture design of the workpiece is essential for elastomer machining experiments. The fixture shown in Figs. 3 and 4 was designed to provide adequate and consistent support for the workpiece. A flat molded rubber workpiece (295 mm × 14.7 mm × 10 mm) was clamped between a base and a top plate. The elastomer material used in this study was the KM rubber, which is a mixture of synthetic and natural elastomers made by Michelin for tire tread applications. The height h on the base was set to be 9.1 mm, which is smaller than the 10 mm thickness of the elastomer plate in order to provide the required clamping force. As shown in Fig. 4, the top plate was designed with seven grooves to allow an end mill to trace across the flat elastomer workpiece with a consistent support pattern for all end milling tests. The top plate was 4.75 mm thick and made of steel. The width of span, w, on the top plate was chosen to be 19.1 mm, making it sufficiently large to accommodate all tools while

![Fig. 2 Up-, down-, and mixed-cut end mills, (a) up-cut end mill, (b) down-cut end mill, (c) mixed-cut end mill, (d) up-cut end milling setup, (e) down-cut end milling setup, and (f) mixed-cut end milling setup](image)
providing adequate structural support. The length of the groove was 134 mm, which was adequate to reach the steady state cutting conditions for end-milling.

4 Finite Element Analysis of the Stiffness of Elastomer Workpiece

The finite element method was used to evaluate and compare the stiffness of the elastomer workpiece, which is constrained by the fixture and machined by three end mills with different diameters. Figures 5 and 6 show the three finite element meshes that were used for modeling the elastomer workpiece held in the fixture described in the previous section for three end mill diameters (3.18, 6.35, and 12.7 mm in diameter). By assuming the cut is in the middle of the groove in the fixture, a symmetric boundary condition was applied to plane FGHIJK so that only half of the workpiece was modeled. The finite element meshes for cutting with 3.18, 6.35, and 12.7 mm diameter end mills are shown in Figs. 5, 6(a), and 6(b), respectively. Two types of three-dimensional elements were used to model the elastomer. One is the 9-node, 27-degree-of-freedom tetrahedral element and another is the 20-node, 60-degree-of-freedom hexahedral element. The ANSYS finite element analysis software and its mesh generator were used in this study.

For all three finite element meshes, nodes along lines AB and DE and the line passing through point C and parallel to line AB and DE are fixed in all three (X, Y, and Z) directions. Due to the symmetry boundary conditions, all nodes on plane FGHIJK have zero displacement in the Y direction and are free to move in X and Z directions. The seven key dimensions of the finite element meshes are denoted from \( l_1 \) to \( l_7 \), as illustrated in Fig. 5. The six parameters, \( l_1 = 19.55 \) mm, \( l_2 = 10 \) mm, \( l_3 = 30 \) mm, \( l_4 = 10 \) mm, \( l_5 = 6.35 \) mm, and \( l_6 = 15 \) mm, are the same for all three meshes. The length \( l_7 \), which equals half of the tool diameter, is the only parameter that varies for these three meshes. The dimensions of \( l_7 \) equals 1.59, 3.18, and 6.35 mm for the mesh in Fig. 5, Fig. 6(a), and Fig. 6(b), respectively. The depth of cut in the finite element model, \( l_5 \), was set at 6.35 mm. It is slightly larger than the 3.81 mm depth of cut set in the end milling experiment. The intent is to model the worst case during the up-cut milling when the workpiece is lift and the depth of cut is increased.

During end milling, the force is concentrated along cutting edges of the end mill. These cutting edges move across the cylindrical surface, represented by GHML in Fig. 5. Note that the actual deformation of the workpiece under such a moving load is dynamic and difficult to analyze. Therefore, a simplified parameter called the effective stiffness, \( k_e \), was defined to allow for a comparison of stiffness for the elastomer workpiece as machined by different end mill diameters. The model assumes a traction stress is uniformly distributed in the Z direction on the quarter cylindrical surface GHML, as shown in Fig. 7(a). This traction stress deforms the workpiece. The displacement at one specific point is selected for the stiffness calculation. The definition of the effective stiffness, \( k_e \), is given by:

\[
k_e = \frac{2F}{d_GZ}
\]

where \( F \) is the resultant force of the uniform traction stress on the quarter cylindrical surface GHML and \( d_GZ \) is the Z direction displacement at point G, which is the middle point of circular arc on the top surface of the workpiece. The force, \( 2F \), in Eq. (1) is equal to the total force applied on the half cylindrical surface.

Fig. 3 The deformation of elastomer workpiece while machining using an up-cut end mill

Fig. 4 Fixture for end milling of elastomer (a) base and top plate with grooves and (b) top view of the fixture with the elastomer workpiece in place

Fig. 5 Three-dimensional finite element meshes and boundary conditions for the elastomer workpiece machined by 3.18 mm diameter end mill

Fig. 6 Finite element meshes and boundary conditions for the elastomer workpiece machined by 6.35 mm diameter end mill

Fig. 7 Finite element meshes and boundary conditions for the elastomer workpiece machined by 12.7 mm diameter end mill

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The effective stiffness \( k_e \) is calculated by first converting the traction stress shown in Fig. 7(a) to the consistent nodal forces on an element surface with eight nodal points. The procedure for determining the consistent nodal forces is described in Cook, et al. [21]. The consistent nodal forces on the eight nodes for a uniformly distributed traction stress with an equivalent element resultant force, \( F_e \), on the surface of an element are shown in Fig. 7(b). These nodal element forces are then assembled for all the elements and applied to the nodes on the quarter cylindrical surface GHML, as shown in Figure 7(c). All nodal forces on the surface GHML are aligned in the \( Z \) direction. An elastic modulus of 2 MPa and Poisson’s ratio of 0.49 are used in the finite element analysis.

A comparison of the computed effective stiffness, \( k_e \), for the three levels of uniformly distributed traction stress of 0.114, 0.285, and 0.570 N/mm\(^2\) for three end mill diameters of 3.18, 6.35, and 12.7 mm are summarized in Table 2. Table 2 also lists the resultant force on the quarter cylinder, \( F \), and the \( Z \)-direction displacement of point G, \( d_{GZ} \), which is calculated using the finite

![Fig. 6 Three-dimensional finite element meshes for the elastomer workpiece machined by end milling with (a) 6.35 mm and (b) 12.7 mm diameter tools](image)

![Fig. 7 Loading on the finite element analysis (a) assuming the traction stress is uniformly distributed on the surface of an element in the \( Z \)-direction, (b) the consistent nodal load at the eight nodes on the surface of a hexahedral element with the element resultant force, \( F_e \), on the surface, and (c) assembled force vectors on the quarter cylinder surface](image)

<table>
<thead>
<tr>
<th>Milling tool diameter (mm)</th>
<th>Traction stress (N/mm(^2))</th>
<th>Resultant force on the quarter cylinder, ( F ) (N)</th>
<th>( Z )-displacement at point G (mm)</th>
<th>Effective stiffness (N/m)</th>
<th>Avg. effective stiffness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>0.114</td>
<td>1.81</td>
<td>0.467</td>
<td>7734</td>
<td>7663</td>
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<tr>
<td></td>
<td>0.285</td>
<td>4.51</td>
<td>1.17</td>
<td>7688</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.570</td>
<td>9.03</td>
<td>2.39</td>
<td>7566</td>
<td></td>
</tr>
<tr>
<td>6.35</td>
<td>0.114</td>
<td>3.61</td>
<td>0.723</td>
<td>9984</td>
<td>9983</td>
</tr>
<tr>
<td></td>
<td>0.285</td>
<td>9.03</td>
<td>1.80</td>
<td>10012</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.570</td>
<td>18.1</td>
<td>3.63</td>
<td>9954</td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>0.114</td>
<td>7.22</td>
<td>12.5</td>
<td>11571</td>
<td>11530</td>
</tr>
<tr>
<td></td>
<td>0.285</td>
<td>18.1</td>
<td>3.14</td>
<td>11509</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.570</td>
<td>36.1</td>
<td>6.27</td>
<td>11511</td>
<td></td>
</tr>
</tbody>
</table>
element method. It was found that the effective stiffness $k_e$ is nearly constant under the three traction stresses for each end mill size. The calculated average effective stiffness is 7663, 9983, and 11530 N/mm for end milling with a 3.18, 6.35, and 12.7 mm diameter tool, respectively. This represents a 30% and 15% improvement of effective stiffness when the size end mill is increased from 3.18 to 6.35 and from 6.35 to 12.7 mm diameter, respectively. The reduction of volume of elastomer material between the tool and fixture using larger diameter end mills is the main reason for the improving structural stiffness of elastomer workpiece seen in Table 2. As shown in the next section, this change in workpiece stiffness has a significant influence on the cleanliness of the machined groove.

The stiffness of a steel workpiece with the same geometry and boundary conditions as in Figs. 5 and 6 was also calculated for comparison. The elastic modulus of 200 GPa and Poisson’s ratio of 0.3 were used. The effective stiffness of the steel workpiece is increased by about 84000 times for three end milling tool diameters. This shows the low structural stiffness of elastomer workpiece. Such drastic reduction in workpiece stiffness has made the fixture design a critical subject for machining of elastomers.

5 Experiment Design

Milling tests were conducted on a HAAS VF1 CNC vertical machining center. The fixture was mounted on a 3-axis Kistler piezoelectric dynamometer to measure components of the end milling forces. All machining tests were conducted dry without any coolant. The depth of cut was set at 3.81 mm for all end milling tests.

Since there is very little information available in the literature pertaining to proper tool selection for elastomer milling, a large number of thirteen end mills was initially selected for testing. These tools represent a wide range of sizes (3.18, 6.35, and 12.7 mm diameter), tool materials (high speed steel and carbide), cutting directions (up-cut and down-cut), number of flutes (single- and double-flute), and cutting edge geometry. Top and side views of these end mills and other basic tool parameters are shown in Fig. 8. These tools are woodworking router bits manufactured by Onsrud Cutter LP. The Onsrud tool number is also listed in Fig. 8 for reference.

Several of these end mills are belong to three series. Tools in a series have the same basic geometry but different diameters. As shown in Fig. 8, the tools in each series are as follows:

- **Series 1**: Tools 1 (3.18 mm) and 6 (6.35 mm)
- **Series 2**: Tools 2 (3.18 mm), 4 (6.35 mm), and 12 (12.7 mm)
- **Series 3**: Tools 7 (6.35 mm) and 13 (12.7 mm)

where the number in parentheses represents the tool diameter. The performance of each series of tools was compared to provide insight into elastomer machining based upon basic tool geometry within each series.
Seven sets of milling experiments were conducted. The process parameters of these experiments are summarized in Table 3. Table 4 summarizes the peripheral cutting speeds and feeds for tests conducted in Experiments I–VII. In Experiment I, thirteen end mills were used to machine a groove in an elastomer workpiece at room temperature. Experiments II and III were conducted under identical conditions, but under reduced temperature conditions. Based on favorable milled groove surfaces achieved in Experiment I for Tool 6, twelve additional tests were conducted with this tool for three rotational speeds ~2900, 4200, and 5500 rpm! and four feed speeds ~2.12, 6.35, 10.6, and 14.8 mm/s! as Experiment IV. In Experiment V, the same additional twelve tests were conducted with an elastomer temperature of ~78.6°C! solid carbon dioxide cooled. Two final series of tests were conducted with an up-cut tool ~Tool 8! for a room temperature and solid carbon dioxide cooled elastomer. A total of 87 end-milling tests were conducted. For each test, chips were collected, cleanliness of the machined groove was recorded, and milling forces were measured.

### 6 Cleanliness of End Milled Grooves

As shown in Fig. 1, the capability of a milling tool to efficiently remove material and generate a neat and burr-free groove is an important performance indicator for tool selection. The surface appearance and cleanliness of the milled cut was recorded using an optical camera with close-up lens and then categorized into four levels as shown in Fig. 9. Level A corresponds to a burr-free and clean groove, which is the best surface. Level B is a clear-milled groove, but with some residual burrs on the surface. Level C is characterized by a thin layer of residual elastomer that covers a clear-milled groove. Level D is a clogged groove which is unacceptable. It is noted that the elastomer material inside the groove was removed for all levels except D. The surface groove condition for all experiments is summarized in Fig. 10 and Table 5. The effect of different process parameters on cleanliness of the groove is discussed in the following sections.

#### 6.1 Effect of Workpiece Stiffness

Four grooves that were machined by Tools 12 and 13 all have the A rating in appearance. Note that these tools have the largest diameter of 12.7 mm. These tests indicate that the effective stiffness of the workpiece, which is larger when machined by larger diameter end mill, is a significant factor in producing a clean groove. In contrast, Tools 2 and 4, which have similar tool geometry as Tool 12 but with a smaller diameter ~3.18 and 6.35 mm in diameter!, did not produce a clean groove. Similarly, Tool 7 ~6.35 mm in diameter!, which has the same tool geometry as Tool 13 ~12.7 mm in diameter! but with a smaller diameter, only produced a B-rated groove. This finding was further confirmed by the poor performance of Tools 1 and 2, which failed to generate a clear-cut groove ~D-rated groove for all three experiments!.

#### 6.2 Effect of Up- and Down-cut Configuration

Tools 6, 12, and 13, all down-cut tools, performed very well as indicated by the A-rated groove that they produced for all Experiments I, II, and III under both room and reduced temperatures. Tools 5 and 7, which are both 6.35 mm diameter down-cut tools, also produced...
good grooves (B-rated) for all Experiments I, II, and III. The
down-cut configuration pushes the chip into the workpiece, which
helps to achieve a clean-cut groove.

6.3 Effect of the Tool Material, Number of Flute, and Helix Angle. Good grooves were produced by the three 6.35 mm
diameter Tools 5, 6, and 7. Since these tools including both carbide and high speed steel tool materials as well as single- and
double-flute tool geometry, no conclusive evidence could be
drawn on the effect of tool material and number of flute on groove condition. The helix angle for tools 6 and 7, both 30 deg, are
high. It confirms the observation of the effect of high helix angle
in elastomer machining [5].

6.4 Effect of Workpiece Temperature. Cooling the elastomer workpiece in solid carbon dioxide improves the effective-
ness of tools for removing elastomer work-material. For some
tools, such as Tools 3, 4, and 8, the improvement was significant.
Comparing the results of groove cleanliness in Experiments I and II, the freezer cooled elastomer (Experiment II) did not show sig-
nificant improvement in groove cleanliness.

6.5 Effect of Feed Speed and Tool Rotational Speed. Tools 6 and 8 were selected for a more complete test matrix at
four feed speeds and three spindle speeds. Both tools have double-
flutes and are made of carbide. Tool 6 has a down-cut and Tool 8
has an up-cut configuration. Table 5 shows results of cleanliness
for Experiments IV (room temperature) and V (solid carbon diox-
ide cooled) by Tool 6 and Experiments VI (room temperature) and
VII (solid carbon dioxide cooled) by Tool 8. The significant ad-

![Table 5: Grooves machined in Experiments I and III](image)
good performance of Tool 6. Note that A-rated grooves were produced at the highest spindle speed in Experiments IV and V. This observation indicates that high cutting speed is beneficial in elastomer machining. It also indicates that high feed rate may not be advantageous for elastomer machining. Some B-rated grooves were observed at high feed speeds at 2900 and 4200 rpm (57.9 and 109.7 m/min peripheral cutting speed) in Experiments IV and V. This is further discussed in Fig. 11.

Figure 11 shows the machined groove corresponding to the four corners of the test matrix in Experiment V, for spindle speeds of 2900 and 5500 rpm (57.9 and 109.7 m/min cutting speed) and feed speeds of 2.12 and 14.8 mm/s (5.78, 11.0, 40.4, cutting speed and 76.6 µm/flute feed). The deterioration of the groove cleanliness to level B at 2900 rpm and 14.8 mm/s (57.9 m/min cutting speed and 76.6 µm/flute feed) in Experiment V can be seen. A comparison of the two grooves machined by Tool 8 in Experiment VII using the same process parameters of 5500 rpm spindle speed (109.7 m/min cutting speed) and 2.12 and 14.8 mm/s feed speeds (5.78 and 40.4 µm/flute feed) are also shown in Fig. 11. Cleaner grooves machined by Tool 6 under the same end milling condition were apparent. Photographs in Fig. 11 also illustrate the deterioration of groove cleanliness at high feed rate while the spindle speed remains the same. This is possibly due to the lack of large enough uncut chip thickness for effective chip generation in elas-

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Tool</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>B</td>
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<td>B</td>
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<tr>
<td>II</td>
<td>D</td>
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<td>B</td>
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<td>C</td>
<td>C</td>
<td>C</td>
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<tr>
<td>III</td>
<td>D</td>
<td>D</td>
<td>D</td>
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<td>A</td>
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<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 5  Cleanliness of the groove in the seven elastomer machining experiments

Legend:
A: Clear groove
B: Clear groove with residual burrs on the surface
C: Thin layer of elastomer on surface covering clear groove
D: Clogged groove

<table>
<thead>
<tr>
<th>Spindle Speed (rpm)</th>
<th>Feed speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2900</td>
<td>2.12  6.35  10.6  14.8</td>
</tr>
<tr>
<td></td>
<td>A      A      B    B</td>
</tr>
<tr>
<td>4200</td>
<td>A      A      A    B</td>
</tr>
<tr>
<td>5500</td>
<td>A      A      A    A</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Spindle Speed (rpm)</th>
<th>Feed speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2900</td>
<td>2.12  6.35  10.6  14.8</td>
</tr>
<tr>
<td></td>
<td>C      C      C    C</td>
</tr>
<tr>
<td>4200</td>
<td>C      C      C    C</td>
</tr>
<tr>
<td>5500</td>
<td>C      C      C    C</td>
</tr>
</tbody>
</table>

Fig. 11 Some grooves machined in Experiments V and VII
tomer machining at high spindle speed. A further discussion of chip morphology is provided in the companion paper [22] to validate this hypothesis.

It is noted in Experiments VI and V that, under the same cutting speed, the width of groove varies at different feed speeds. Higher feed speed generates narrower groove width. The large elastic deformation and rebound of the elastomer workpiece during the end milling are possible causes for the variation in groove width.

7 Concluding Remarks

The end milling of elastomers using sharp woodworking router bits was presented in this paper. A set of 13 different tools with various diameters, materials, number of flutes, and up- and down-cutting configurations were tested on room temperature and solid carbon dioxide cooled elastomers. This study observed that Tools 6, 12, and 13, all down-cut tools, performed well in generating clean grooves on the elastomer workpiece. The stiffness of the elastomer workpiece was proven to be critical to influence the performance of end milling. Three-dimensional finite element analysis was used to study the stiffness of the elastomer workpiece held in the fixture designed and built for this study.

This study concludes that the sharp, down-cut tool configuration and stiffness of the elastomer workpiece are the two most important variables that influence the effectiveness in end milling to remove elastomer work-material and generate a clean groove. With proper selection of end mill geometry, process parameters, and fixture stiffness, clean grooves can be machined on the elastomer workpiece. The workpiece temperature is also an important variable. Cryogenic cooling of the elastomer workpiece can help enhance the performance of end mills that do not perform well on machining room temperature elastomer workpiece. This study also confirms that higher spindle speed is beneficial for machining a clean groove in elastomers.

End milling has complicated tool geometry and is not suitable to study the basic mechanics on elastomer machining. Orthogonal cutting with defined tool rake angle and tip radius is more suitable to investigate the fundamentals of elastomer cutting mechanics. This is an on-going research [23,24].

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