1. INTRODUCTION

Milling is one of the most conventional machining processes used in the industry. Also, it is one of the most complex processes of metals by cutting, because the milling cutter, as well as multi-cutter tool, presents a more complex operation compared to turning and drilling process, not only because of the large number of cutting edges, but also because of the variability of intersection of the chips while a tooth is processing. This process is influenced by many output parameters and one of the most important parameters is the temperature because it affects the tool wear and tool life. Cutting tools are expensive and have a duration of cutting edges, but also because of the variability of the chips during the machining process is of the great importance for the understanding and optimization of process parameters.

In addition, it is believed that after turning, milling process is the most common in removing material. The most common is face milling with milling heads and end milling. The end milling is one of the typical interruptible processes. In the process, since the cutting tool repeats cutting material and air cutting, the temperature of cutting tool repeats heat up and cooling down. Cutting temperature is an important parameter because alternating heating and cooling of cutting tools affects the tool wear and surface quality.

To determine cutting temperature or temperature fields in end milling we can use different methods. Due to the complexity of milling processing main difficulties in measuring cutting temperature during the milling is because of the following: the tool rotates and teeth tools entering into engagement with the workpiece in and out of it; area covered with heat moves across the surface of the workpiece; chips can interfere with the measuring [1, 2].

Over the past decades large number of experimental methods have been developed because of these difficulties such as mathematical simulations that use numerical methods. Alternative approaches have been developed because of these difficulties such as mathematical simulations that use numerical methods. It turned out that the numerical methods are not always the most appropriate method in terms of the recording of the temperature. High quality thermographic equipment offers the highest acceptable level of accuracy of the estimates, although this method can be inaccurate because of changes in the emission coefficient and the possibility that chips with its position shelters the area whose temperature is measured.

The experimental approach for studying treatment process is expensive and time-consuming especially when it includes a wide range of tool geometry, materials and processing parameters. Alternative approaches have been developed because of these difficulties such as mathematical simulations that use numerical methods. It turned out that the numerical
finite element methods are most useful and widely used. The proper selection of FEM software is very important for determining the scope and quality of analysis that will be performed. For the simulation processing is used software package Third Wave advantedge.

2. EXPERIMENTAL SETUP FOR END MILLING

The experiments were conducted on a vertical CNC machining center in dry cutting conditions. Dimensions of the workpiece were 50 × 20 × 10 millimeters of AISI 4340 steel with the material properties according to Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>785 ( kg/m³)</td>
</tr>
<tr>
<td>Melting point</td>
<td>1450 (°C)</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>208 (GPa)</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Specific heat</td>
<td>477 (J/kg°C)</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>44.5 (W/m°C)</td>
</tr>
</tbody>
</table>

Table 1. AISI 4340 steel material properties

Tests used an uncoated tungsten carbide end mill model with 10 mm of diameter, length of 72 mm, depth of cut of 22 mm, and number of flutes of 4. The workpieces were painted black due to the emissivity. The machining operation is done for the cutting conditions shown in Table 2.

<table>
<thead>
<tr>
<th>Cutting conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spindle speed, n</td>
<td>2200 (rev/min)</td>
</tr>
<tr>
<td>Feed per tooth, f</td>
<td>0.040 (mm/tooth)</td>
</tr>
<tr>
<td>Axial depth of cut, a_p</td>
<td>1 (mm)</td>
</tr>
<tr>
<td>Radial depth of cut, a_e</td>
<td>2 (mm)</td>
</tr>
</tbody>
</table>

Table 2. Selected machining parameters in experiment

Figure 1 shows the experiment’s setup. The data acquisition of temperature was done using a FLIR InfraCAM Wester infrared camera, with an accuracy of 0.1°C. The assembly of the infrared camera was at 300 mm from the heat source.

Figure 2 shows temperature that was recorded on the end of the workpiece.

3. FEM TOOL FOR CUTTING PROCESS

In the research field of cutting process, the finite element method is regarded as a very useful tool to study the cutting process of materials [3]. Finite Element Method (FEM) permits the prediction of cutting forces, stresses, tool wear, and temperatures of the cutting process so that the cutting tool can be designed. The right choice of finite element software is very important in determining the scope and quality of the analysis that will be performed [4]. One of the most important software packages used for simulation of metal cutting is Third Wave AdvanEdge.

Third Wave AdvanEdge is a special program written for machining simulations. It is developed based on the dynamic explicit Lagrangian formulation. The model is built by selecting the type of machining operation (e.g. turning, broaching, sawing or milling) and defining the necessary process parameters [5]. AdvanEdge contains a user-friendly interface and offers the possibility of creating new tool and workpiece geometries within the program and also to import complex geometries from other CAD files. Also allows users to import complex geometries and have extensive material library and allows specifying new materials uses adaptive meshing to increase the accuracy of solution. In AdvanEdge simulations can run in demonstration mode, decreases the simulation time but is less accurate and standard mode, requires longer simulation time but is more accurate [6].

AdvanEdge utilizes Tecplot software to display and assist in analyzing simulation results [7]. The Tecplot displays and assists in analyzing the simulation results. Among the displayed results there can be enumerated: chip formation, chip and tool temperature, cutting forces, steady state variables such as: strain, stress, strain von Misses, etc [6].

4. FEA SIMULATION OF END MILLING

According to the experiments presented in the previous section, a 10 mm diameter end mill have been
designed with SolidWorks. After that, one more simplified end mill model is created in the aim to give a coarser mesh and based on that reduce the duration of the simulation. In both cases it is taken into account only cutting part of the mill participating in machining. Then end mill models were exported in STL files and imported into AdvantEdge. Figure 3 shows the end mills model imported in AdvantEdge.

![End mills imported in AdvantEdge](image)

Fig. 3. End mills imported in AdvantEdge

Workpiece material AISI 4340 steel and tool material Carbide-General were selected from the library of 3D materials. Workpiece model was reduced regards to the workpiece from the experiment due to better mesh generation. Figure 4 shows model of complex end mill and the workpiece in AdvantEdge before starting the simulation.

![End mill and workpiece in AdvantEdge](image)

Fig. 4. End mill and workpiece in AdvantEdge

In AdvantEdge users have the option to alter the workpiece meshing parameters; however, these modifications may affect performance and accuracy. Meshing parameters selected within the Workpiece Meshing tab of the 3D Simulation Options window are important for successful 3D simulations. Minimum element edge length and the radius of regined region values are calculated differently depending on the process. In milling, these values are calculated using maximum chip load based on the feed per tooth and the radial depth of cut. For all of these processes, these meshing values will be recalculated every time the process parameters for these simulations are changed [6]. If a simulation crashes, for any reason, a new simulation can start where the previous stopped.

4.1 Simulation results

Two simulations were run in demonstration mode without changes in Workpiece Meshing. First simulation used simplified end mill. Second simulation used complex end mill in order to get more accurate simulation results. Cutting conditions used in the simulation correspond to the processing parameters in the experiment. The calculation time is approximately 3 days for simulation with simplified end mill and 7 days for simulation complex end mill. Simulation worked on a HP xw8600 workstation with 2 x CPU of 4 physical cores each, meaning a total of 8 physical cores and 16 GB RAM.

Figure 5 and 6 show the FEM model of milling operation and temperature distribution for cutting conditions from Table 2.

![Temperature distribution during simulation 1](image)

Fig. 5. Temperature distribution during simulation 1

The Contour tab of the AdvantEdge Quick Analysis window is used to select contour displays in Tecplot. The different colors on the tool represent different levels of temperature.

![Temperature distribution during simulation 2](image)

Fig. 6. Temperature distribution during simulation 2

Using Tecplot software it can be seen different steps during the simulation. It is possible to observe the chip formation during a tooth path. Figure 7 and 8 present the temperature contours on end mill, work piece and chips. A contour level is a value at which contour lines are drawn, or for banded contour flooding, the border between different colors of flooding [8].

![Temperature contours on chips obtained through simulation results](image)

Fig. 6. Temperature contours on chips obtained through simulation results
4.2 Simulations vs. experiment

The variation of temperature distribution between FEA simulations and experimental work are shown in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Exp. Result</th>
<th>FEA Result</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation No.1</td>
<td>161.4 °C</td>
<td>115.1 °C</td>
<td>-28.68%</td>
</tr>
<tr>
<td>Simulation No.2</td>
<td>161.4 °C</td>
<td>181.8 °C</td>
<td>12.64%</td>
</tr>
</tbody>
</table>

Table 3. Results comparison

By comparing the experiment and the simulations showed that the error for the first simulation of -28.68% and for the second simulation 12.64%.

5. CONCLUSION

Simulation of milling in AdvantEdge allows analyzing temperature in the cutting zone and permit obtaining reliable data for the experiment validation. The error between experimental work and simulation by FEA is in the range of ±30%. Accurate modeling of the end mill geometry should be used to improve the numerical prediction of cutting temperature even though it has a significant impact on increasing the duration of the simulation. The results of the work can be used for optimizing the parameters of milling operation of AISI 4340 steel.

6. REFERENCES


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