Research Article

Numerical Modelling, Simulation, and Analysis of the End-Milling Process Using DEFORM-3D with Experimental Validation

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In this present work, finite element analysis (FEA)-based simulation of end-milling of AISI1045 steel using tungsten carbide tool was performed using DEFORM-3D simulation software. Usui tool wear model, Johnson-cook material model and adaptive remeshing are considered during machining simulation. The impact of machining variables rate of feed, tool speed, and depth of cut was investigated, and the best integration of variables was distinguished for lower cutting temperature, principal stress, cutting forces, effective stresses, tool wear, and effective strain. The obtained results were correlated using experimentation in a vertical machining center attached with a Kistler tool dynamometer with data acquisition setup for capturing the cutting forces, and an infrared (IR) thermometer was used to measure the cutting temperature, and a comparison was done. Results showed a good correlation. There is a relationship between experimental and numerical results, and simulation findings can be utilised for interpreting the influence of machining parameters.

1. Introduction

The development of several computational strategies for tackling engineering problems has resulted from the revolution in computer technology over the last few decades. Mathematical modelling has become an important part of engineering problem analysis, and several numerical methods were created, including the finite element method (FEM), the finite difference method (FDM), the boundary element method (BEM), and the finite volume method (FVM) [1]. FEM is one of the most adaptable and versatile engineering problem-solving techniques. To gain information, simulation is the recreation of dynamic procedures in a model that may be applied in real life. Cutting forces, morphology of chips, stresses, strains, and temperatures can all be determined using simulation earlier than actual machining using a cutting tool. Modelling and experiments also contribute to a better understanding of fundamental problems in machining theory [2]. Mechanics of milling includes the shearing between the workpiece and the edge of the cutting tool, the effect of friction between the chip and the rake face of the tool, and ploughing action between the machined surface and the cleared surface. Cutting forces are generated by the cumulative impact of the three components, which can induce deflection in cutting and can cause additional damage to the machined part surface quality [3].

Jing et al. [4] performed simulation studies on microend-milling for developing an ideal cutting force mechanics model and found the momentary thickness of uncut chip by taking the runout of the tool, least chip thickness, the trajectory of the tool, and the elastic recovery rate of the workpiece and discovered that the forces of cutting were affected by the elastic recovery rate. Pragadish et al. [5] considered the Johnson–Cook materials model for cutting
From the performed literature, it is concluded that 3D-FEM simulation of end-milling process quality characteristics depends on the selected material, parameters of tool geometry, and machining parameters along with the material model. Correlation of simulation studies with experimental results is carried out widely, but 3D-FEM analysis of end-milling cutter is scarce in literature. Numerical simulation of AISI 1045 steel under end-milling conditions is conducted in this work, which was not considered previously by researchers as per our knowledge. Moreover, measurement of the interface temperature and cutting forces experimentally and its correlation with simulation studies are limitedly reported by various researchers for different conditions of machining. Hence, an attempt has been made to perform the simulation of the end-milling process for different machining conditions and to determine the cutting forces acting during machining and machining temperature. 3D simulation of the end-milling process is not studied experimentally and its correlation with simulation studies are limitly reported by various researchers for different conditions of machining. Hence, an attempt has been made to perform the simulation of the end-milling process for different machining conditions and to determine the cutting forces acting during machining and machining temperature. 3D simulation of the end-milling process is not studied experimentally and its correlation with simulation studies are limitedly reported by various researchers for different conditions of machining. Hence, an attempt has been made to perform the simulation of the end-milling process for different machining conditions and to determine the cutting forces acting during machining and machining temperature. 3D simulation of the end-milling process is not studied experimentally and its correlation with simulation studies are limitedly reported by various researchers for different conditions of machining. Hence, an attempt has been made to perform the simulation of the end-milling process for different machining conditions and to determine the cutting forces acting during machining and machining temperature. 3D simulation of the end-milling process is not studied experimentally and its correlation with simulation studies are limitedly reported by various researchers for different conditions of machining. Hence, an attempt has been made to perform the simulation of the end-milling process for different machining conditions and to determine the cutting forces acting during machining and machining temperature. 3D simulation of the end-milling process is not studied experimentally and its correlation with simulation studies are limitedly reported by various researchers for different conditions of machining.
delays associated with shop trials [22, 23]. Open die forging, closed die forging, extrusion, rolling, cogging, drawing, machining, compaction, extrusion, and upsetting are all common applications.

Figure 2 shows the modeled milling cutter and workpiece using DEFORM-3D. Initially, the cutter is modeled for a diameter of 8 mm, length of 20 mm, and a helix angle of 45°. Then, the workpiece is generated with a 50 mm diameter, with a starting angle of 0° and an arc angle of 30°. The relative mesh technique is adopted for workpiece and tool meshing [24], and simulation has been performed with 25000 elements which are sufficient to give an accurate model of the cutter. The edges of the workpiece are fixed in all directions [25, 26]. For the end-milling tool, the surface mesh is generated with 5482 polygons and 2743 points, and the solid mesh is generated with 21383 elements and 5170 nodes with dynamic zooming. For the workpiece, the solid mesh is generated with 20365 elements and 4886 nodes with dynamic zooming.

The region between the workpiece and the tip of the tool where the contact is made has a finer mesh. Initially, the Lagrangian incremental methodology is used to solve the problem, and then steady-state machining is performed. The workpiece is considered a thermo-viscoplastic deformable body with isotropic behaviour. The Johnson–Cook material model was considered which is a temperature and strain rate dependent model that describes thermo-mechanical behaviour of material flow over the entire range of strain rate and temperature as given in the equation for equivalent flow stress [27, 28].

\[
\sigma = (A + B\epsilon^m) \left(1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right) \left[1 - \left(\frac{T - T_T}{T_m - T_T}\right)^n\right],
\]

where \(T, \sigma, \dot{\epsilon}, \epsilon\) indicate equivalent temperature, flow stress, rate of plastic strain, and plastic strain. The yield stress at the initial condition is \(A\), the hardening modulus is \(B\), the exponent of strain hardening is \(n\), and the sensitivity coefficient of strain rate is \(C\). \(T_T\) is the reference temperature which is equal to 20°C, and \(T_m\) is the melting temperature which is equal to 1520°C. The Cockcroft–Latham fracture criterion was employed in this chip separation study [6], which is the total damage calculated with the equivalent strain and maximum principal stress, as shown in the equation. To represent the quantity of ductile damage, only one material constant is required. As a result, the material constant can only be ascertained by experimental investigation [29, 30].
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where $\sigma_{\text{max}}$ is the maximum principal stress, $\varepsilon$ is the equivalent strain, $\varepsilon_f$ is the equivalent strain at which the fracture occurs, and $C_1$ is the material constant for ductile damage. Adaptive meshing is a remesh technique in which an old deformed mesh is replaced with a new one. Smoothing shifts nodes to produce more standard element configurations, whereas refinement enhances the density of mesh by decreasing the size of mesh [31, 32]. Adaptive meshing enhances simulation accuracy. The wear rate at the contact surface is determined by relative velocity, constant pressure, and absolute temperature in Usui’s model of tool wear as given in the following equation:

$$\frac{dw}{dt} = A\sigma_u V e^{-B/T}.$$  

(3)

Figure 3: Simulation results of the end-milling process.
The wear rate simulation constants are $A = 0.0000000078$ and $B = 5302$ [33].

### 3. Results and Discussions

For performing simulation of the end-milling process, spindle speeds are varied as 70, 85, 100, 115, and 130 m/min, feed rates are varied as 0.1, 0.125, 0.15, 0.175, and 0.2 mm/rev, and the depths of cut are varied as 0.5, 0.75, 1.0, 1.25, and 1.5 mm, and the machining process is analyzed numerically. During the simulation of the end-milling process, the environment temperature is defined as 30°C. The heat exchange is usually very small because the cutter process happens very quickly (<1sec). The tool-workpiece interface parameters such as the
shear friction factor and heat transfer coefficient are not varied or not considered during the analysis. Initially, simulation is performed for transient conditions, and after the required steps are completed, steady-state machining is performed, and the outputs are measured [34]. After the end of the simulation, the values of the parameters such as mean stress, effective stress, effective strain, maximum principal stress, and temperature are taken from it, and the graphs are developed on a timely basis. Figure 3 displays the various stages captured during the simulation of the end-milling process, temperature rising during machining along with the contact of the milling tool with the workpiece, and the formation of the chip from the workpiece.

After performing simulation in a transient condition, and after the required length is cut, machining is carried out in a steady-state condition [35]. The output responses such as interface pressure, interface temperature, resultant cutting forces, and wear rate were...
measured, and a comparison was performed. Figure 4 presents the comparison of output responses for different conditions of rotational speed. It is observed that a linear increase in output conditions was seen, with an increase in rotation speed, due to the higher material removal and friction that exists between the tool and the workpiece.

The change in output values for different feed rates of the end-milling tool during simulation is presented in Figure 5. With increase in feed rate values from 0.1 mm/rev to 0.2 mm/rev, output values also tend to increase. Initially, with a change in feed rate value from 0.1 to 0.125 mm/rev, an abrupt increase in the interface temperature is visualized, followed by interface pressure due to the higher load acting on the tool, which obviously increases the pressure and friction between the tool and the workpiece. Similarly, milling forces tend to increase with the increase in the feed rate [36–38].

Figure 6 displays the variation of interface pressure, interface temperature, resultant cutting force, and wear rate obtained with a variation in the depth of cut. An increase in interface temperature, interface pressure, and resultant
cutting force is observed, and simultaneously a reduction in the wear rate is obtained with an increase in the depth of cut values [39–42].

The variation of cutting temperature during the simulation process for different rotational speeds is shown in Figure 7. It is visualized that at initial conditions of milling, a steep increase in temperature takes place during the extreme friction between the cutting tool and the workpiece arising from the shearing action of the tool on the workpiece [43]. The trend of different rotational speeds is similar. Similarly, for change in the feed rate as presented in Figure 8, the cutting temperature is similar except for a feed rate of 0.1 mm/rev. With a lower feed rate, the pressure between the workpiece and the tool gets lowered, and hence, a lower cutting temperature is sensed. But with higher feed rates, pressure tends to increase which subsequently increases the cutting temperature [44]. A similar trend is also observed for change in depth of cut in Figure 9, the cutting temperature is lower for 0.5 mm of depth of cut, and for other depths of cut, it is higher.

For validating the results obtained from simulation studies, a set of experiments are performed with 100 m/min of

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Figure 10: Photographic view of VMC used for machining.

Figure 11: Experimental cutting force.
tool rotation, 1 mm of the depth of cut, and 0.15 mm/rev of the rate of feed. The experiment is performed with the WC end-milling tool in a vertical machining center (VMC) attached with a cutting force dynamometer integrated with a data acquisition system connected with a personal computer, which is shown in Figure 10. Cutting forces are measured using a piezoelectric type Kistler dynamometer (9257B type) having ranges of Fx, Fy, and Fz between $-5 \text{kN}$ and $+5 \text{kN}$ with a threshold value of $<0.01 \text{N}$, a natural frequency of $f_n(x,y,z)$ kHz $\approx 3, 5$, and an operating temperature ranging from 0°C to 70°C with a clamping area of $100 \times 170 \text{mm}$ [45].

The METRAVIMT-9 IR thermometer with dual laser is utilised to determine the milling temperature that has a measuring range of $-50^\circ \text{C}$ to $1000^\circ \text{C}$, 0 to $50^\circ \text{C}$ working temperature, and a response time of 150 ms [46].

Figure 11 shows the components of cutting force obtained during the machining process. At the initial stages of machining, cutting forces tend to increase abruptly, after which it tends to stabilize around a specific value [47].

The temperature obtained during milling from the experimental and numerical methods is compared as presented in Figure 12, and it was found that a close correlation exists between them for variation in considered milling parameters [28, 48]. Experimental results show that with the increasing rotational speed of the end-milling cutter, the interface temperature tends to rise due to the higher friction that exists between the carbide cutter and the workpiece as no lubrication is added during machining. Similarly, an increase in the feed rate obviously increases the cutting temperature sharply. A drastic rise in cutting temperature is observed with higher feed rates [49]. Increasing the depth of cut of machining increases the friction as more material is removed through shearing action which eventually increases the cutting temperature as illustrated in Figure 12.

4. Conclusion

In this work, milling process simulation is performed to study the behavior of the milling cutter using Deform-3D.
The temperature distribution, effective stress, and maximum effective stress in the cutter, workpiece, and chip are studied and analyzed. The simulation result helps to analyze the performance of AISI 1045 steel during end-milling process with tungsten carbide tool. With the change in the feed rate, an increase in the interface temperature and interface pressure is observed due to the higher load acting on the tool, which obviously increases the pressure and friction between the tool and the workpiece. Similarly, milling forces tend to rise with a higher rate of feed. Higher pressure and temperature at the interface with increased resultant force are observed, and simultaneously, a reduction in the wear rate is obtained with an increase in the depth of cut values.

At initial conditions of milling, a steep increase in temperature takes place during extreme friction between the cutting tool and the workpiece arising from the shearing action of the tool on the workpiece. With a lower feed rate, the pressure between the workpiece and the tool gets lowered, and hence, a lower cutting temperature is sensed. But with higher feed rates, pressure tends to increase which subsequently increases the cutting temperature.

The comparison of cutting temperature between the experimental and numerical analyses has a close correlation between variation in the rate of feed, speed of milling cutter, and depth of cut.

**Data Availability**

The data used to support the findings of this study are included within the article and are available from the corresponding author upon reasonable request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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