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Research Article

S. Sai Venkatesh*, T. A. Ram Kumar, A. P. Blalakumhren, M. Saimurugan, and K. Prakash Marimuthu

Finite element simulation and experimental validation of the effect of tool wear on cutting forces in turning operation

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Abstract: Machining is the most widely used process in manufacturing, and tool wear plays a significant role in machining efficiency and effectiveness. There is a continuous requirement to manufacture high-quality products at a lower cost. Many past researches show that variations in tool geometry affect the cutting forces significantly. The increase in cutting forces leads to excessive vibrations in the system, giving a poor surface finish to the machined product. In this work, a 2D coupled thermo-mechanical model is developed using Abaqus/Explicit to predict the cutting forces during turning of mild steel. Johnson–Cook material model along with damage model has been used to define the material behavior. Coulomb's friction model is considered for defining the interaction between the tool and the work piece. Metal cutting process is simulated for different sets of cutting conditions and compared with experimental results. The finite element method results correlate well with the experimental results.

Keywords: Machining, Coupled thermo-mechanical model, FEM, Abaqus/Explicit

1 Introduction

Tool wear influences tool life, machining cost, and most importantly the machining quality. Thus a quantitative study of cutting forces is essential for tool life estimation and tool condition monitoring. Initially, experimental methods and analytical methods were used to study cutting forces. D'Mello *et al.* [1] investigated the effects of flank wear, cutting parameters, and tool vibrations on the surface roughness during high-speed turning of Ti–6Al–4V. Ning *et al.* [2] devised a set of turning experiments with tool inserts having different tool edge radii from 2 to 62 µm and studied the effects of tool edge wear on cutting forces in Inconel 718. However, with advances in computational techniques, studies are now focused toward using numerical methods such as finite element method (FEM) for analysis. Krishnakumar *et al.* [3] studied the effects of residual stresses on AISI 4340 steel during multiple pass turning and the FE model was validated with the experimental results. Thepsonthi *et al.* [4] studied the effects of tool edge radius on the machining performance of end-milling process. Both 2D and 3D models were used to predict the temperature and cutting forces developed during machining. The FEM results were validated with the experimental results. It is found that both models predict comparable results for cutting forces but there is a significant difference in cutting temperatures because of quicker dissipation of heat in the 3D model.

Each tool has a different wear profile and it is not possible to obtain a single unique wear profile for a tool. Thus, the present work introduces a predefined artificial wear at the tip of the tool by EDM process. The same change is incorporated into the tool in Abaqus model. The simulations are performed for three different sets of conditions and the results are validated. The cutting conditions are listed in Table 1.

Table 1: Cutting Condition.

Description	Speed (RPM)	Feed (mm/rev)	Depth of Cut (mm)	Wear (mm)
Condition 1	630	0.16	0.2	0
Condition 2	630	0.16	0.5	0
Condition 3	630	0.16	0.2	0.4

***Corresponding Author: S. Sai Venkatesh:** Department of Mechanical Engineering, Amrita University, Coimbatore, India; Email: prakashkmuthu@gmail.com
T. A. Ram Kumar, A. P. Blalakumhren, M. Saimurugan, K. Prakash Marimuthu: Department of Mechanical Engineering, Amrita University, Coimbatore, India

2 Finite Element Simulation

Researchers have used numerical simulations for studying various structural and flow phenomena [5–9]. Finite element simulation has been very helpful in predicting forces, residual stresses, wear and tear of tool, and temperature variation during the machining processes [6, 8–15]. Apart from machining, simulation researchers have been using finite element simulation extensively [16, 17]. The present work uses finite element simulation to study force variation during the turning process using both a good and a worn-out tool. Future work involves optimization of the machining parameters for reduced forces using statistical tools [18, 19].

2.1 Basic description of the model

The present work develops a fully thermo-mechanical coupled 2D plane strain finite element turning model for mild steel using Abaqus/Explicit software. This thermo-mechanical model is very much essential to understand the effect of temperature on the machining process and wear process [20, 21]. The simulation is carried out for three different sets of conditions as mentioned in Table 1. The work piece is defined as deformable and the tool is defined as discrete rigid. A rigid modeling tool reduces solution time and does not greatly affect the accuracy of the solution. The work piece and both the good and the defective tools are shown in Figure 1 and Figure 2, respectively. The cutting duration is chosen as 0.002 seconds to reduce computational time. Arbitrary Lagrangian Eulerian (ALE) technique is used for meshing to smoothen out excessive distortions in mesh and maintain a good mesh quality during cutting process. This is discussed in detail in Section 2.4.

Figure 1: Work piece modeled as a deformable body.

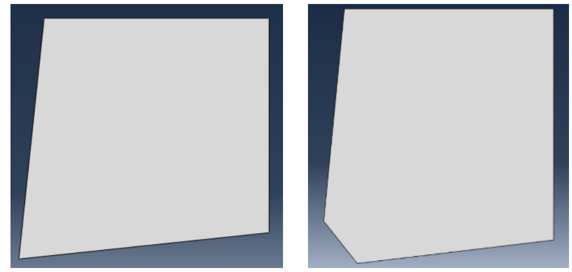

Figure 2: Tool modeled as a good tool and tool modeled as a worn-out tool.

2.2 Material behavior

In metal cutting process, the work piece is subjected to very high temperature, strain, and strain rates. Therefore it is necessary to include these effects while developing the model. Thus, a thermo-viscoelastic model is required for the analysis of a machining process. There are several empirical models developed to model material flow stress properties. Johnson–Cook model is the most prominent and widely used model in metal cutting process. Johnson–Cook model [22, 23] is expressed as

$$\sigma = [A + B\epsilon^n]\left[1 + Cln\frac{\acute{\epsilon}}{\acute{\epsilon}_o}\right]\left[1 - \frac{T - T_o}{T - T_m}\right] \tag{1}$$

where σ is the material flow stress, ϵ is the equivalent plastic strain, $\acute{\epsilon}$ is the strain rate, $\acute{\epsilon}_o$ is the reference plastic strain, T is the temperature of the work piece material, T_o is the reference temperature, and T_m is the melting temperature of the work piece material. The first term in the equation includes the effect of the previous strain present in the material, the second term includes the effects of strain rate, and the last term includes the effects of thermal softening. A, B, C, n, and m are Johnson–Cook constants which are found out experimentally. Because these experiments are highly advanced and complex and the dedicated labs for such experiments are very few in India, these values are obtained from existing literature. Tables 2 and 3 show Johnson–Cook constants and material properties of mild steel, respectively.

Table 2: Johnson–Cook material properties of mild steel.

A	*B*	*C*	*n*	*m*
148 MPa	341 MPa	0.01	0.183	0.859

Table 3: Material properties of mild steel.

Parameter	Value
Young's modulus	210 GPa
Poisson's ratio	0.3
Specific heat	432 J/kg/°C
Thermal conductivity	47.7 W/m °C
Density	7800 kg/m^3
Friction coefficient	0.3

2.3 Damage criteria

The damage criteria define the criteria for separation of chip from the parent metal. An appropriate choice of damage model and criteria is required to achieve the desired results. Most damage models define a critical value for the effective plastic strain, exceeding which the material cracks and fails. There are several ductile fracture models available in the literature. The most widely used model is the Johnson–Cook damage model [24], because of its simplicity, ease of calibration of constants, and availability of fracture constants for many metals.

$$\epsilon_f = [D_1 + D_2 \exp(D_3\sigma^\star)][1 + D_4 \ln(\dot{\epsilon}^\star)] \left[1 + D_5\left(\frac{T - T_o}{T - T_m}\right)\right] \tag{2}$$

where $\sigma^\star$ is the ratio of average of three normal stresses to von Mises equivalent stress, $\dot{\epsilon}^\star$ is the dimensionless strain rate, T is the material temperature, T_o is the reference temperature, T_m is the melting temperature, and D_1, D_2, D_3, D_4, and D_5 are fracture constants. The first set of brackets includes the effect of triaxiality, the second set of brackets includes the effect of strain rate, and the third set of brackets includes the temperature effects. The damage parameter D is given by

$$D = \frac{\Delta\overline{\epsilon v}}{\epsilon_{failure}} \tag{3}$$

where $\Delta\epsilon_p$ is the incremental strain. When damage parameter D exceeds 1.0, the material fractures and fails. Table 4 shows the Johnson–Cook damage constants for mild steel.

Table 4: Johnson–Cook material properties of mild steel.

D_1	D_2	D_3	D_4	D_5
0.071	1.248	−1.142	0.147	0.1

2.4 Choice of element type and meshing

The element type used for the analysis is CPE4RT. It is a four-node, plane strain, coupled bi-linear temperature-displacement element with a global element size of 0.02.

In machining process, the material undergoes a large deformation where the mesh is unable to give accurate results and often results in termination of analysis. ALE is a new meshing technique used to prevent excessive distortion in the element. In ALE, the distorted mesh is smoothed at regular intervals, keeping the mesh size, number of elements, and their topology unaltered.

In Lagrangian approach the nodes move with the material points. It is easy to track free surfaces and apply boundary conditions but it results in a distorted mesh at high strain gradients. It can be used to analyze transient problems. In Eulerian approach the nodes remain fixed and the material flows through the mesh resulting in no mesh distortion. This approach is usually used in fluid flow analysis. This approach is used for the analysis of steady-state problem. Chip separation cannot be simulated in this approach. In ALE approach the nodes are constrained to material motion only where necessary. In other cases, they remain independent. This approach combines the benefits of both types of approaches without their drawbacks and is mostly used in applications involving large deformation. Figure 3 shows the meshed work piece and tool.

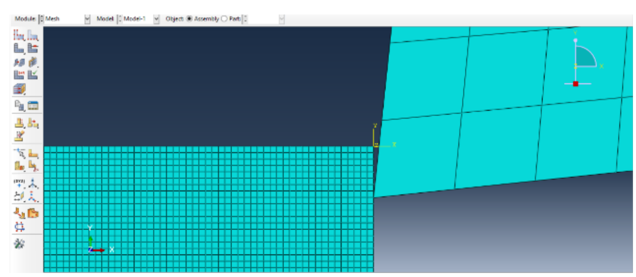

Figure 3: Meshed model of the work piece and the tool.

2.5 Work piece and tool interaction

Tool interaction is a very important parameter in chip formation and achieving the desired outcome. The contact type used is "Surface to Surface" contact. The tool and the work piece form a contact pair. The tool surface is defined as "Master Surface" and work piece surface is defined as "Slave Surface." This prevents the nodes from slave surface penetrating into the master surface. Coulomb's friction law is used in this model, assuming a constant friction coefficient of 0.3. Figure 4 shows the interaction between the tool and the work piece.

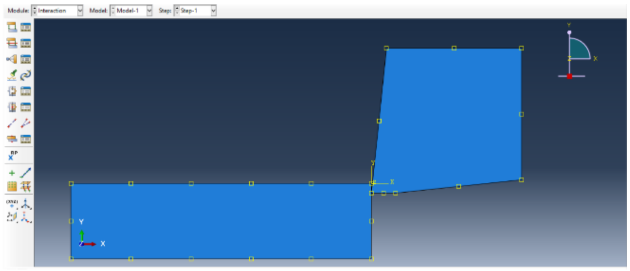

Figure 4: Surface to surface interaction established between the tool and the work piece.

2.6 Finite element simulation

Many researchers have done finite element simulation in order to study the different details of the cutting process which includes chip formation, temperature variation, force variation, and residual stresses analysis [15, 25–28]. Figure 5 and Figure 6 show chip formation for the two conditions—good tool and worn-out tool.

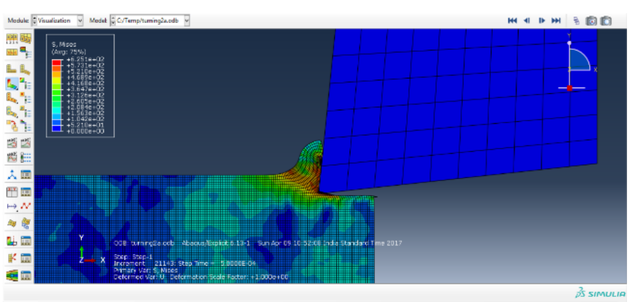

Figure 5: Chip formation obtained using a good tool.

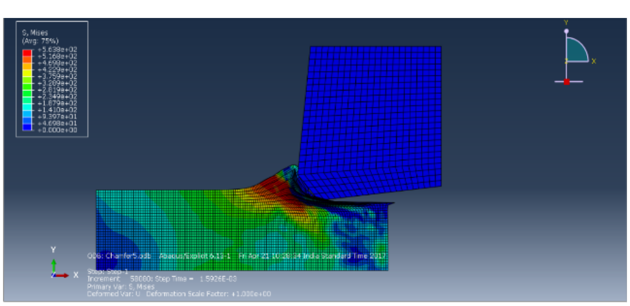

Figure 6: Chip formation obtained with the worn-out tool.

Scaling factor is a technique to decrease computational time. A large scale factor may decrease computational time to a large extent but the final results can be affected significantly. The scaling factor has to be chosen without any compromise on the results. By trial and error method, the scaling factor was defined as 1000 for this analysis. The simulations were performed for three different sets of conditions. Chip formations were successfully obtained for all different cutting conditions. The cutting force data obtained from the analysis was plotted in Excel and the mean cutting force was calculated for all the conditions. Figures 7-9 show the variation of cutting force for the three sets of conditions.

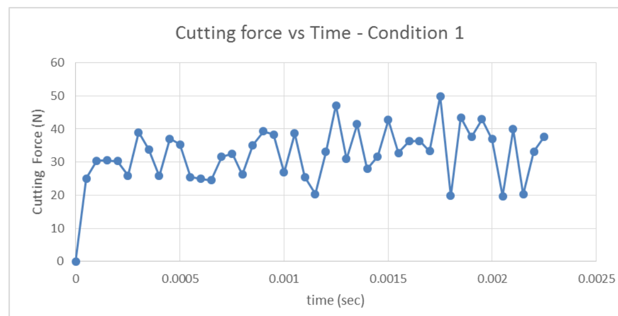

Figure 7: Cutting force variation with respect to time—condition 1.

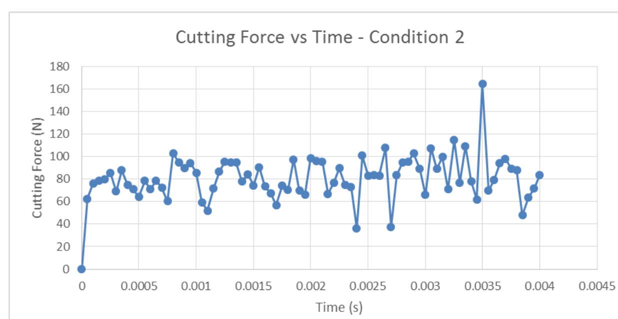

Figure 8: Cutting force variation with respect to time—condition 2.

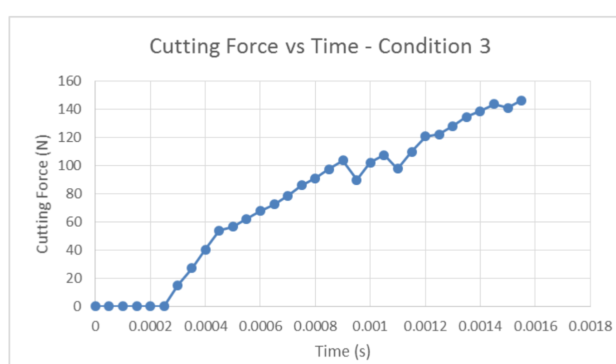

Figure 9: Cutting force variation with respect to time—condition 3.

3 Experimental Validation

The turning operation was performed using conventional lathe. The cutting parameters are listed in Table 5. The wear is artificially induced by making a change in the tool's profile by EDM process. The work piece used for machining is mild steel. Tungsten carbide insert, which has two cutting edges, is used. One edge of the tool is a new tool whereas the other's profile is changed in order to provide a wear of 0.4 mm. The insert is shown in Figure 10.

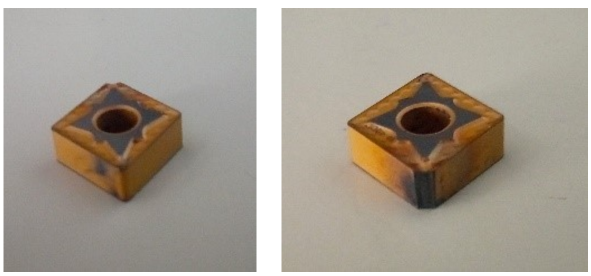

Figure 10: Good tool (left), worn tool (Right).

The cutting force in turning operation is determined using a strain gauge. Here, the strain gauges are connected in half-bridge configuration type II. This configuration was specifically designed for measuring bending strain. In this configuration, two strain gauges are bonded to two opposite surfaces of the tool holder. The strain gauges are then connected to DAQ NI-9237. The acquired data from DAQ are processed using Lab-View software and the mean strain readings are obtained. The tool holder is assumed to be a cantilever beam and, from the bending equation for beams, the bending stress is determined. By Hooke's law, cutting force is calculated from bending stress.

4 Results and Discussion

The 2D finite element simulation of turning operation was accomplished using Abaqus/Explicit. Both the simulation and the experiment were performed under the same cutting conditions. Based on tool parameters mentioned in Table 5, the cutting force is calculated.

Comparison between the experimental and the finite element results is shown in Figure 11.

Table 5: Tool parameters

Parameter	Value
Breadth of tool section (b)	0.025 m
Height of the tool section (h)	0.025 m
Distance of top surface from neutral layer (y)	0.0125 m
Area moment of inertia of section (I) is given by ($bh^3/12$)	3.25521×10^{-8} m^4
Section modulus (Z) is given by (I/y)	2.60417×10^{-6} m^3
Young's modulus of tool holder (E)	2.05×10^{11} N/m^2
Distance from tool tip to center of strain gauge	0.045 m
Work piece diameter	0.03 m

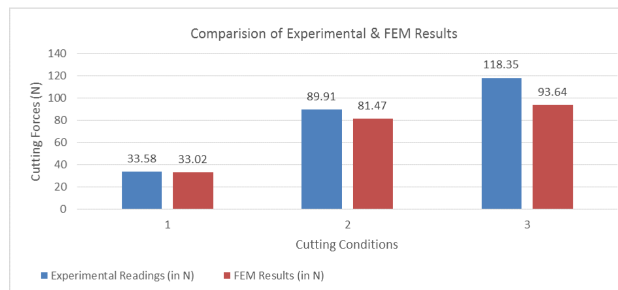

Figure 11: Comparison between experimental and finite element results.

5 Conclusion and Future Scope

Based on the results obtained from the experiment and finite element simulation, the following conclusions are drawn. The finite element results correlates with the experimental results for no wear condition with less than 10% error. The maximum percentage of error is 9.4%.

Thus, the finite element model is a better model for predicting cutting forces. This method can save time and cost when compared to experimental method. There is a large scope in future to improve the accuracy of the model through

(a) developing a 3D model [29], which can predict results more accurately because of lesser number of assumptions
(b) modeling the tool as viscoelastic instead of treating it as rigid
(c) developing alternate friction models to predict the cutting forces

References

[1] D'Mello, G., Pai, P. S., Puneet, N. P. and Fang, N.: Surface roughness evaluation using cutting vibrations in high speed turning of Ti-6Al-4V - an experimental approach, International Journal of Machining and Machinability of Materials, vol. 18, pp. 288-312, 2016.

[2] Fang, N., Pai, P. S. and Mosquea, S.: Effect of tool edge wear on the cutting forces and vibrations in high-speed finish machining of Inconel 718: an experimental study and wavelet transform analysis, The International Journal of Advanced Manufacturing Technology, vol. 52, pp. 65-77, 2010.

[3] Krishnakumar, P., Prakash Marimuthu, K., Rameshkumar, K. and Ramachandran, K. I.: Finite element simulation of effect of residual stresses during orthogonal machining using ALE approach, Int. J. Machining and Machinability of Materials, vol. 14, pp. 213-219, 2013-2014 2013.

[4] Thepsonthi, T. and Özel, T.: 3-D finite element process simulation of micro-end milling Ti-6Al-4V titanium alloy: Experimental validations on chip flow and tool wear, Journal of Materials Processing Technology, vol. 221, pp. 128-145, 2015.

[5] Bharathwaj, R., Giridharan, P., Karthick, K., Prasath, C. H. and Prakash Marimuthu, K.: Computational study of Coanda based Fluidic Thrust Vectoring system for optimising Coanda geometry, IOP Conference Series: Materials Science and Engineering, vol. 149, p. 012210, 2016-2017 2016.

[6] Kumar, B. V. R. M., Hemachandra Reddy, K. and Vikram Kumar, C. R.: Finite Element Model Based On Abaqus / Explicit To Analyze The Temperature Effects Of Turning, International Journal of Applied Engineering Research, vol. 11, pp. 5728-5734, 2016.

[7] Meyappan, P. L., Akhila Roy, Abhijith, J., Ramesh, M. N. V. and Prakash Marimuthu, K.: Tsunami Wave Impact on Structures, International Journal of Applied Engineering Research, vol. 10, pp. 1135-1139, 2014-2015 2015.

[8] Salahshoor, M. and Guo, Y. B.: Finite Element Simulation and Experimental Validation of Residual Stresses in High Speed Dry Milling of Biodegradable Mg-Ca Alloys, Procedia CIRP, vol. 14, pp. 281-286, 2014.

[9] Scippa, A., Grossi, N. and Campatelli, G.: FEM based Cutting Velocity Selection for Thin Walled Part Machining, Procedia CIRP, vol. 14, pp. 287-292, 2014.

[10] Boob, G. R., Deoghare, A. B., Walke, P. V. and Padole, P. M.: Numerical modelling and simulation of orthogonal machining process using FE-code, International Journal of Machining and Machinability of Materials, vol. 17, pp. 370-380, 2015.

[11] Chen, L., El-Wardany, T. I. and Harris, W. C.: Modelling the Effects of Flank Wear Land and Chip Formation on Residual Stresses, CIRP Annals - Manufacturing Technology, vol. 53, pp. 95-98, 2004.

[12] Das, S. R., Dhupal, D. and Kumar, A.: Experimental investigation on cutting force and surface roughness in machining of hardened aisi 52100 steel using cbn tool, 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014) December 12th–14th, 2014, IIT Guwahati, Assam, India, 2014.

[13] Lu, J., Chen, J., Fang, Q., Liu, B., Liu, Y. and Jin, T.: Finite element simulation for Ti-6Al-4V alloy deformation near the exit of orthogonal cutting, The International Journal of Advanced Manufacturing Technology, vol. 85, pp. 2377-2388, 2015.

[14] Salvatore, F., Saad, S. and Hamdi, H.: Modeling and Simulation of Tool Wear During the Cutting Process, Procedia CIRP, vol. 8, pp. 305-310, 2013.

[15] Xi, Y., Bermingham, M., Wang, G. and Dargusch, M.: Finite Element Modeling of Cutting Force and Chip Formation During Thermally Assisted Machining of Ti6Al4V Alloy, Journal of Manufacturing Science and Engineering, vol. 135, p. 061014, 2013.

[16] Kailasam, R., Yuvaperiyasamy, M., Premkumar, R. and Dhanabal, M.: FEA of Chrome{Nickel Composite in Engine Valve Guides, Mechanics and Mechanical Engineering, vol. 21, pp. 5-10, 2017.

[17] Lykhachova, O.: Numerical Simulation of Axially Compressed Cylindrical Shells with Circular Cutouts, Mechanics and Mechanical Engineering, vol. 20, pp. 309-321, 2016.

[18] Marichamy, S., Saravanan, M., Ravichandran, M. and Stalin, B.: Optimization of Surface Roughness for Duplex Brass Alloy in EDM Using Response Surface Methodology, Mechanics and Mechanical Engineering, vol. 21, pp. 57-66, 2017.

[19] Selvaraj, J., Prakash Marimuthu, K., Devanathan, S. and Ramachandran, K. I.: Mathematical modelling of raw material preheating by energy recycling method in metal casting process, Pollution Research, vol. 36, pp. 217-228, 2017.

[20] Shanmughasundaram, P.: Effect of Temperature, Load and Sliding Velocity on the Wear Behavior of AA7075–SIC Composites, Mechanics and Mechanical Engineering, vol. 21, pp. 85-93, 2016.

[21] Sharma, R., Jadon, V. K. and Singh, B.: Thermo Mechanical Deformation and Stress Analysis of Hydroxyapatite/Titanium FGM plate by FEM, Mechanics and Mechanical Engineering, vol. 20, pp. 499-513, 2017.

[22] Kartik, B., Abishek, R., Kaliyannan, D. and Prakash Marimuthu, K.: Numerical Simulation of Low Velocity Impact Analysis of Fibre Metal Laminates, Mechanics and Mechanical Engineering, vol. 20, pp. 515-530, 2016.

[23] Milani, A. S., Dabboussi, W., Nemes, J. A. and Abeyaratne, R. C.: An improved multi-objective identification of Johnson–Cook material parameters, International Journal of Impact Engineering, vol. 36, pp. 294-302, 2// 2009.

[24] Pramod, M., Reddy, Y. G. and Prakash Marimuthu, K.: Prediction of machining induced residual stresses, AIP Conference Proceedings, vol. 1859, 2017.

[25] Nasr, M. N. A.: Effects of Sequential Cuts on Residual Stresses when Orthogonal Cutting Steel AISI 1045, Procedia CIRP, vol. 31, pp. 118-123, 2015.

[26] Valiorgue, F., Rech, J., Hamdi, H., Gilles, P. and Bergheau, J. M.: A new approach for the modelling of residual stresses induced by turning of 316L, Journal of Materials Processing Technology, vol. 191, pp. 270-273, 2007.

[27] Movahhedy, M. R., Gadala, M. S. and Altintas, Y.: Simulation of Chip Formation in Orthogonal Metal Cutting Process: An Ale Finite Element Approach, Machining Science and Technology, vol. 4, pp. 15-42, 2000.

[28] Prakash Marimuthu, K., Thirtha Prasada, H. P. and Chethan Kumar, C. S.: Force, Stress prediction in drilling of AISI 1045 steel using Finite Element Modelling, IOP Conf. Ser.: Mater. Sci. Eng, vol. 225, 012030, 2017.

[29] Prakash Marimuthu, K., Thirtha Prasada, H. P. and Chethan Kumar, C. S.: 3d Finite Element Model To Predict Machining Induced Residual Stresses Using Arbitrary Lagrangian Eulerian Approach, Journal of Engineering Science and Technology, in press.