Finite Element Modelling of Temperature in Machining of Duplex Stainless Steel (DSS) 2205

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Abstract. Duplex stainless steels (DSSs) are a group of austenitic – ferritic stainless steels featuring an excellent resistance to corrosion and mechanical strength, which makes them the most suitable material to be used in highly corrosive environments. The superior chemical and mechanical properties of DSSs are a result of excessive alloying which renders them very poor machinability. Low machinability combined with high hardness of DSSs generate high temperatures during machining. Exposure to elevated temperatures induces embrittlement, the formation of unwanted intermetallic precipitates and microstructural changes. The high amount of heat generated also shortens the tool life, leads to higher surface roughness and dimensional sensitivity. Hence it is important to study the temperature distribution generated during machining of DSS. In this work, Finite Element modelling and simulation (ABAQUS) for orthogonal and oblique cutting of DSS 2205 was developed using explicit temperature dynamic analysis and meshing was based on Lagrangian formulation. Johnson-Cook material model has been utilized for defining flow stress of the work material. The model developed was validated by experiments conducted using coated WC cutting inserts and the temperatures were measured using thermal camera and thermocouple setup. It was found that the simulated values were able to follow the pattern of the experimental results. The change in temperature distribution due to the coating on the tool was studied.

Keywords: Finite Element modelling, Temperature, ABAQUS, Duplex Stainless Steel, Lagrangian

1. Introduction

There is always a constant search in the manufacturing field for materials having more and more mechanical strength and corrosion resistant. The family of Duplex Stainless Steels has stood out to be one of the pioneers in this search. They have a dual phase microstructure with nearly equal proportions of austenite and ferrite and possessing combined properties of the two phases.

Due to the high amount of alloying elements (Cr, Mo, Ni), they showcase an extremely desirable combination of superior properties like high strength, high corrosion resistance, good weldability, high stress corrosion cracking and high pitting resistance equivalent (PRE value more than 40). This makes them the most suitable material to be used in extremely harsh and corrosive
environments demanding superiority in both chemical and mechanical aspects. Hence they are the most preferred material when it comes to usage in aggressive areas like offshore oil and gas exploration, petroleum industries, refineries, paper and pulp industries, chemical treatment plants, desalination plants and a range of marine and architectural applications.

However, the demerit of the excessive alloying is that DSSs have a quite low machinability, making them difficult to machine. Due to the low machinability and high hardness, the temperatures and forces associated with machining of DSSs are expected to be very high. The generation of high heat however brings some more problems at the same time it is a challenging task to measure the exact temperature generated during machining. It has been seen that if DSSs are exposed to high temperatures, they undergo microstructural changes and what is known as 475°C embrittlement. Apart from this, temperatures above 300°C also result in formation of some intermetallic phases like gamma, alpha and sigma phase, which are detrimental to the material’s strength and corrosion resistance. Hence it is very important to study the temperature distribution in DSSs during machining.

Grzesik. W et al. [1] considered orthogonal cutting process for developing a simulation model by means of coated and uncoated WC tools using explicit finite element method Thirfwave AdvantEdge. The number of layers were progressively increased in thin layers that is TiC, TiN, and Al2O3 films which was deposited on WC tool. Finite element solutions such as cutting force, and temperature were checked for its applicability of the simulation models. They observed that the temperature distribution was influenced by interfacial friction between tool and chip. The effect of coating on temperature fields were also studied. Mishra. S. K et al. [2] focused their study on the effect of textured tools on the residual stresses and temperature during turning of titanium alloy. The effect of TiAlN coating and texturing on the residual stresses and temperature generated during machining were studied through 2D and 3D finite element modeling. The results of the simulation showed that lower temperature and residual stresses were produced during the turning process with textured TiAlN coated tool. Özel. T et al. [3] investigated the cutting force, temperature, chip formation and tool wear using 3D finite element simulation. Coated carbide inserts were used with TiAIN and TiAIN+cBN coatings. Material model was developed considering strain softening effect. Xiangyu Teng et al. [4] developed a simulation model with focus on the cutting mechanisms during the machining of magnesium based MMCs with nano particles (SiC) reinforced into it. ABAQUS/Explicit is utilized for simulating 2D model considering cutting edge radius effect. Chip formation, cutting forces and tool-particle interaction were focused in this study. For orthogonal machining of AISI 1045 steel, Özel and Zeren [5] used Arbitrary Lagrangian Eulerian (ALE) method for modeling plastic flow around the cutting tool and for elastic plastic work deformations they utilized the Johnson-Cook (JC) model. Chip formation, temperature were the major findings.

In the present work, the finite element simulation model for simulating the temperature distributing in machining of Duplex Stainless Steel 2205 considering the edge radius and the effect of coating in the insert was developed using dynamic temperature explicit analysis in ABAQUS. Lagrangian formulation was used for mesh generation. Johnson Cook material model has been utilized for defining the flow stress of the work material. The results of the simulation were compared with the experiments performed using CNMG 120408 MM MC7015 grade CVD coated turning insert and the temperatures were measured using thermal camera and thermocouple setup. The effect of Al2O3 film coating on the temperature distribution in the tool was also studied.

2. Finite element modelling of Turning process
Finite element simulation package (ABAQUS 6.14) was used for the developing the simulation model model for temperature generated in turning of DSS 2205. The thermal effects were incorporated by performing a coupled thermo mechanical analysis by selecting the step type as “Dynamic Explicit Temp” and meshing was based on Lagrangian formulation.
Fig. 1 (a) Boundary condition (b) Meshing of workpiece and tool

The upper part of mesh was made finer to achieve good accuracy in the modelling. The workpiece was modelled with 97567 four-noded quadrilateral elements and the element size is 50μm. The boundary condition and meshing are shown in Fig. 1. The tool is considered to be deformable (with in the elastic limit) and is allowed to move only in X direction but the work piece is restricted in all directions. The mechanical and thermal properties of the cutting tool is given in table 2. And coefficient of friction was taken as 0.25. [7]

Fig. 2 (a) Boundary conditions (b) Meshing of workpiece and tool

In order to describe the workpiece material behaviour of duplex stainless steel Johnson Cook material model was utilized which best suits for machining simulations due to its applicability under high strain rates and temperature. [6]

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\bar{\sigma}_{JC} = [A + B(\dot{\epsilon})^{n}] \times \left[1 + Cln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0}\right)\right] \times \left[1 - \left(\frac{T-T_0}{T_m-T_0}\right)^m\right]
\]  

(1)

Where, \( \bar{\sigma}_{JC} \) is the flow stress, \( \dot{\epsilon}_0 \) is reference plastic strain rate which is 1/s \( \epsilon \) and \( \dot{\epsilon} \) are equivalent plastic strain and equivalent plastic strain rate respectively. A, B, C, n, m are JC material constants and its values are given in Table 1. The contact was defined between the rake surface and nodes of the workpiece material. The interaction parameters such as coefficient of friction was taken as 0.25 in the present study to model the friction condition as the chip flows over the rake surface. Similarly, 3D finite element system was modelled as shown in the Fig. 2 where the workpiece was considered to be a tube to simplify the model and reduce the computational time. The workpiece was given the rotational motion and the cutting tool was given feed motion. Here the workpiece was modelled with 2170000 quadrilateral (Coupled temperature displacement - CPE4RT) elements and element size was 50μm. The boundary conditions for 3D system are shown in the Fig. 2(a). Thermal properties like specific heat and thermal
conductivity was provided to both tool and workpiece and the system was maintained at an initial temperature of 27°C.

Table 1. Johnson Cook parameters for DSS 2205 [6]

| Parameter     | Value  |
|---------------|--------|
| A (MPa)       | 514    |
| B (MPa)       | 612.96 |
| C             | 0.01194|
| n             | 0.1801 |
| m             | 0.9765 |
| $T_{melt}$ (°C) | 1443   |

Table 2. Mechanical and thermal properties of the tool [2]

| Properties                           | WC    |
|--------------------------------------|-------|
| Density (Kg/m$^3$)                   | 14,900|
| Young’s Modulus (Pa)                 | 6.45e$^{11}$ |
| Poisson ratio                        | 0.24  |
| Thermal conductivity (W/m C)         | 91    |
| Specific heat (J/Kg C)               | 206   |

3. Experimental setup

The turning experiments were performed on a CNC lathe. The workpiece used was a DSS 2205 which was having a diameter of 60mm and 150 mm in length. Machining was done for different values of...
cutting speeds under dry conditions using tungsten carbide cutting insert of ISO CNMG 120408MM MC7015 grade (coating type CVD with coating layers TiCN+Al₂O₃). The tool holder used for machining was DCLNL2525M12. The temperature were measured using the FLIR thermal imaging camera as well as the thermocouple setup.

3.1.1. Temperature measurement. For measuring the temperature during the machining process, a thermocouple was inserted inside the cutting insert as shown in the Fig. 4a and the hole of 1 mm diameter will be made in the cutting insert using EDM. The CAD model of the insert with hole is given in Fig. 4b. Since the hole to be drilled was inclined to both horizontal and vertical plane it was difficult to place the insert on the EDM bed without the fixture. So a fixture was designed in CATIA V5 and it was 3D printed using fused deposition modeling technique (Fig. 5a).

The thermocouple should be placed close to rake face so that the temperature measured will be close to the actual temperature during the machining process. So, this can be achieved by the above processes and it was observed that the thermocouple was placed at a distance of 528.22μm from the rake face as shown in the Fig. 5(b).

4. Results and Discussions
The Finite Element Simulation was developed for turning process of DSS 2205 using ABAQUS. The simulation was performed for various cutting speed and constant feed and depth of 0.2 mm/rev and 1 mm respectively.
Fig. 6 (a) 2D Simulation results at $V = 113.04$ m/min (b) 3D Simulation results at $V = 113.04$ m/min

Fig. 6 shows the temperature distribution obtained from the 2D and 3D simulation developed for a particular cutting speed and feed. It was observed that the temperature increased with the cutting speed and were maximum at the tip of the tool and on rake face where there is continuous flow of chip over it. The simulation results are validated through series of experiments where the temperatures are measured using the FLIR thermal camera and the thermocouple setup. Emissivity value of 0.3 has been used for the thermal imager [8] Fig. 7 shows the temperature generated during the turning process for cutting speeds, $113.04$ m/min, and $56.52$ m/min at a particular feed and depth was maintained $1$mm. The temperatures were also measured using the thermocouple at $528.22\mu$m from the rake face and it was compared with the simulation results which is shown in Fig. 9.

Fig. 7 Thermal images obtained from FLIR thermal camera at (a) $V = 113.04$ m/min (b) $V = 56.52$ m/min
The tool which has been used in the experiment is CVD coated which is having multi-layer coating (TiCN + Al₂O₃). So the effect of coating was also considered in the simulation model and the results of the simulation for both plane and coated tool which was performed at a cutting speed, feed and depth of cut of 131.88 m/min, 0.2 mm/rev and 1 mm respectively is shown (Fig. 10). It was observed from the isotherms that the temperature within the cutting tool is relatively less in case of coated cutting tool when it compared to plane cutting tool this is due to the resistance offered by the coating to the conduction of heat.
As the use of Duplex Steel grades are becoming increasingly inevitable in modern industries like chemical and marine sectors, this work presents an attempt to predict the temperature of DSS 2205 under various machining conditions. Since duplex steels are known to undergo detrimental changes like embrittlement at elevated temperatures, predicting temperatures during machining will help in deciding the appropriate cutting parameters such that these problems can be avoided and hence the overall machinability can be improved.

Conclusion

In this work, thermo mechanical finite element model for orthogonal and oblique cutting was developed incorporating thermal properties of the tool and workpiece for predicting the temperature during turning of Duplex stainless steel 2205 using ABAQUS/Explicit 6.18. This FE model was able to predict the variation of temperature generated during the turning operation for various cutting speeds. The simulated results were validated with the experimental values measured using both thermal camera and thermocouple setup and it was observed that the model was able to follow the pattern developed by the experimental results. The effect of coating was incorporated in the model and it shows that there was reduction in the temperature within the tool. But, the accuracy of the model can be increased by using the appropriate interaction parameters and heat partition between tool and work material. Presence of coating on the tool results in variation of coefficient of friction between tool and workpiece when compared to plain carbide tool and DSS.

References

[1] Grzesik, W., Bartoszuk, M. and Nieslony, P. ” Finite element modelling of temperature distribution in the cutting zone in turning processes with differently coated tools.” Journal of Materials Processing Technology Vol. 164-165 (2005): pp. 1204-1211.
[2] Mishra, S. M., Ghosh, S. and Aravindan, S.” Finite element investigations on temperature and residual stresses during machining Ti6Al4V alloy using TiAlN coated plain and textured tools.” Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10): pp. 979-982. IIT Madras, Chennai, December 2017.
[3] Ozel, T., Sima, M., Srivastava, A. K., and Kaftanoglu, B. “Investigations on the effects of multi-layered coated inserts in machining Ti–6Al–4V alloy with experiments and finite element simulations.” CIRP Annals - Manufacturing Technology Vol. 59 (2010): pp. 77-82.

[4] Teng, X., Huo, D., Chen, W., Wong, E., Zheng, L., Shyha, I., “Finite element modelling on cutting mechanism of nano Mg/SiC metal matrix composites considering cutting edge radius.” Journal of Manufacturing Processes Vol. 32 (2018): pp. 116-126.

[5] Ozel, T., and Zeren, E., “Finite Element Method Simulation of Machining of AISI 1045 Steel With A Round Edge Cutting Tool” Proceedings of 8th CIRP International Workshop on Modeling of Machining Operations, Chemnitz, Germany May 10-11, 2005: pp. 533-542.

[6] Koyee, R., Schmauder, S., Heisel, U., Eisseler, R., “Numerical modeling and optimization of machining duplex stainless steels.” Production & Manufacturing Research Vol. 3 (2015) pp. 36-83.

[7] Grzesik, Wit. Advanced machining processes of metallic materials: theory, modelling and applications. Elsevier, 2008.

[8] Gamarra, J.R. & Diniz, A.E., Taper turning of super duplex stainless steel: tool life, tool wear and workpiece surface roughness, J Braz. Soc. Mech. Sci. Eng. (2018): pp. 323-340.

[9] Nomani, J., Pramanik, A., Hilditch, T., Littlefair, G., “Machinability study of first generation duplex (2205), second generation duplex (2507) and austenite stainless steel during drilling process,” Wear 304 (2013): pp. 20-28.

[10] Krołczyk, G.M., Nieslony, P., Maruda, R.W., Wojciechowski, S., Dry cutting effect in turning of duplex stainless steel as a key factor in clean production, Journal of Clean Production 142 (2017): pp. 3343-3354.

[11] Selvaraj, D. P., Chandramohan, P., Mohanraj, M., Optimization of surface roughness, cutting force and tool wear of nitrogen alloyed duplex stainless steel in a dry turning process using Taguchi method, Measurement 49 (2014) 205-215.