Finite Element Modelling of Cutting Forces in Face Milling of Duplex Stainless Steel 2205

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Abstract. Duplex Stainless Steels are one of the newest pioneers in the world of super alloys. They exhibit a unique combination of high strength and corrosion resistance and hence are currently giving a strong competition to other nickel based alloys and titanium alloys. Due to the excessive alloying of DSSs, they have a very poor machinability, as result of which the cutting forces associated with machining is very high. In this work, a 3D Finite Element Modelling of cutting forces in milling of DSS 2205 has been developed using FEM software package ABAQUS. Oblique cutting has been used so that inaccuracies due to the assumptions in orthogonal machining are avoided. The developed FEM model has been validated experimentally by conduction a series of milling tests. The model results showed close agreement with the experimental results and the forces values were found to be affected most by feed rate. As feed rate per tooth increases, the forces components were also found to be increasing both for experimental and model values.

1. Introduction
As the oil and gas exploration is moving further and further offshore, the need for super alloys having high corrosion resistance along with mechanical strength is growing very fast. The search for such alloys has resulted in the development of the family of Duplex Stainless Steels. They exhibit an extraordinary combination of superior chemical and mechanical properties. They are finding their way through many modern high end applications like petrochemicals, oil refineries, chemical plants, valves, heat exchangers and marine applications. The unique properties showcased by DSS is the result of its high amount of alloying elements. But this high alloying also results in a poor machinability. This in turn yields high cutting forces in machining of DSS. Cutting forces significantly affect many other associated factors like temperature generated, tool wear, power requirements and machine dynamics. Also cutting forces are one of those output factors which are directly influenced by any change in input parameters. Hence it is very important to study the cutting forces in DSS.

Wu and Zhang [1] studied stress distribution, forces, temperatures and chip formation in milling of Ti6Al4V. They developed 3D FEM model using real tool geometry and taking tool as rigid. They found that feed has significant effect on Fx and Fy but no effect on Fz. In another work, Mebrahitom et al.[2] tool Aluminium 6010 as the workpiece and developed an orthogonal model using ABAQUS considering the helix angle of the tool cutter. The simulation and experimentation were done for measuring Fx and Fy since the axial force is negligible. The maximum error percent between the model and experiment was found to be 0.52% for tangential and 22.5% for radial forces. Zhang et al.
[3] developed and validated experimentally a 3D FEM model for a machining a hot worked tool steel with a circular insert. Only cutting edge was modelled and a cambered surface was generated to simulate the pre machined workpiece. The effect of various cutting parameters on the cutting forces and the temperature generated was studied and it was observed that the effect of cutting speed on the forces was negligible while feed rate was the significant factor for Fz component. In yet another work, Nieslony et al. [4] developed a 3D FEM model and studied the cutting power and specific cutting energy as function of cutter rotation angle. The cutting power was found to be increased when cutter rotation forwards and specific cutting energy when the uncut chip thickness was minimum. Gao et al. [5] adopted a coupled Eulerian Langrangian approach and gave a sinusoidal profile to workpiece to achieve a varying uncut chip thickness in the cutting process. They studied the forces and chip geometry for machining of Al6061-T6 and it was observed that the predicted cutting forces have greater relative errors in the vertical direction.

This work aims at creating a much more 3D realistic simulation model by taking even the tool as deformable. The Johnson Cook material constitutive model has been taken as the material plasticity model and the JC material damage criterion as the chip separation criterion. The contact between the tool and the workpiece is taken care of by the Coulomb’s law of friction. The simulation is carried out by the FEM software package of ABAQUS, Explicit. The model is validated by carrying out experiments on DSS 2205 by coated Tungsten Carbide insert.

2. Development of Milling Finite Element Model

2.1. 3D FE model
A dynamic 3D FE model is created for the milling operation of DSS 2205 with the help of FE software ABAQUS with a step time of 0.06 seconds. One insert is used for machining to simplify the model and reduce the computational time without compromising with the simulation accuracy. WIDIA made milling Carbide insert of ISO SDMT 1204PDRML is used for the milling operation. The sketch map of the milling cutter and insert is shown in Fig. 1. To bring the model closer to reality the workpiece is modelled as a cambered pre machined surface and only the cutting strip has been modelled. The boundary conditions and meshing are shown in Fig. 2. Workpiece is kept fixed and rotation and feed is given to the insert. Type of element used is C3D8RT (Hex, 8 node linear brick element with reduced integration and hourglass control), and total no. of hex elements is 285000. Fine meshing has been employed in the model (mesh size: 0.0001 mm), i.e., to enhance the precision of the simulation, the mesh in the machining zone is refined. Axial depth of cut (doc) is 1 mm and the milling is done in dry condition. Room temperature is used as the initial simulation temperature. The insert also has been taken as deformable, contrary to previous models where the tool is assumed as rigid.

| Cutting edges | D  | L10 | S   | BS  | Re |
|---------------|----|-----|-----|-----|----|
|               | 4  | 12.7| 4.77| 1.1 | 1.2|

Fig. 1 Sketch map of milling insert
2.2 Material constitutive model

DSS 2205 has been used as the workpiece material. The chemical composition and mechanical properties of the material are listed in Table 1 and Table 2. Out of various material constitutive models like Litonski-Batra Model, Power Law Model, Bodner-Partom Model, etc, Johnson-Cook Model has been adopted to describe the plastic behaviour of the material as it consolidates strain hardening effect, the effect of strain rate strengthening, and the effect of temperature softening. It can be employed to the dynamic problems where large deformation, high strain rate effect and high temperature are prevalent. The flow stress of material is given by Eq. (1).

\[ \sigma = [A + B(\varepsilon)^n] \times [1 + C \ln \left( \frac{\varepsilon}{\varepsilon_0} \right)] \times \left[ 1 - \left( \frac{T - T_0}{T_m - T_0} \right)^m \right] \]  

(1)

Where \( n \) and \( m \) are the strain hardening and thermal softening index respectively, \( A \) represents the yield strength sensitivity, \( B \) is the strain sensitivity and \( C \) is the strain rate sensitivity of the material. \( \sigma \), \( \varepsilon \), \( \dot{\varepsilon} \), \( \varepsilon_0 \), \( T_0 \), and \( T_m \) are the equivalent stress, equivalent strain, plastic strain rate, reference strain rate, reference temperature and melting temperature respectively. The J-C parameters values for DSS 2205 used in the simulation are tabulated in Table 3.

Table 1. Chemical composition of DSS 2205 [6]

| Element | Weight % |
|---------|----------|
| C       | 0.015    |
| Cr      | 24.92    |
| Ni      | 6.91     |
| Mo      | 4.06     |
| Si      | 0.25     |
| N       | 0.3      |
| P       | 0.021    |
| S       | 0.0007   |
| Cu      | 0.1      |
Table 2. Mechanical properties of DSS 2205 [6]

| Property               | Value |
|------------------------|-------|
| Yield Strength (MPa)   | 579   |
| Tensile Strength (MPa) | 826   |
| Hardness (BHN)         | 236   |
| Elongation             | 40    |

Table 3. Johnson-Cook (J-C) material model parameters for DSS 2205 [6]

| Parameter | Value |
|-----------|-------|
| A (MPa)   | 514   |
| B (MPa)   | 612.96|
| C         | 0.01194|
| n         | 0.1801|
| m         | 0.9765|
| \(\dot{\varepsilon}_0\) | 1     |
| T_melt (°C) | 1443 |

Ductile damage criterion was used as the material damage criterion to simulate chip separation where the damage parameters such as Stress triaxiality and strain rate were identified from tensile tests.

2.3 Contact Model
Friction between chip and rake surface is a very significant contact property as it has an influence on the FEM simulation results. Coulomb’s law is chosen as the contact model where frictional sliding force is directly proportional to the applied normal load. It is given by Eq. (2).

\[ \tau = \mu \sigma \]  
(2)

Where \( \mu \) is frictional stress, \( \sigma \) is normal stress and \( \mu \) is friction coefficient (value of 0.3 is taken in simulation.) [7].

3. Simulation Process
The 3D Finite Element simulation model is developed by the FE package ABAQUS for milling operation. The milling conditions used in the modelling are cutting depth of cut (doc) of 0.8 mm, feed per tooth (fz) of 0.09 mm/tooth and spindle speed (N) of 202 rpm. To simplify the model and reduce the computational time, only up-milling is considered in the simulation process. Since the milling process has many complications, the analysis step was set as “Dynamic, explicit.”
The FEM model results showing the chip formation and stress distribution in milling simulation is given in Fig. 3. Maximum stress occurs in the primary shear band and this primary shear band of chip could be observed clearly when the cutting edge of the milling insert digs into the workpiece.

4. Experimental Validation

To validate the FE model developed, an experimental plan was created and the milling tests were carried out on CNC 4-axis Vertical machining center, Agni BMV45 TC24 having maximum spindle speed as 6000 rpm and FANUC OiMC control system. Workpiece of dimensions 100*150*20 mm and WIDIA made milling carbide insert of ISO SDMT 1204PDRML are used for the milling tests. The insert has a coating of WS40PM grade grade (Multiphase AlTiN-TiN PVD coating on an advanced alloyed substrate) which is suitable for alloys like DSSs. To improve the accuracy of the validation, only up-milling, i.e., 50 % engagement is considered in experimentation as done in the simulation. Milling cutter of WIDAX M690 having a diameter of 63 mm is used and only one insert is used for cutting to make the experiment similar to the simulation model. The corresponding feed calculations are done as per Eq. (3). The cutting parameters used in the experimentation are spindle speed: 202 RPM, feed per tooth: 0.01, 0.03, 0.05, 0.07, and 0.09 mm/tooth, axial depth of cut of 0.8 mm.

\[ f_{\text{min}} = f_z \left( \frac{\text{mm}}{\text{tooth}} \right) \times N(\text{RPM}) \times z(\text{no. of teeth}) \]  

(3)

For measurements of the force components, multi-component Kistler Dynamometer 9257B is used along with charge amplifier and data acquisition system. Dynoware software is used to extract the force data. The full experimental set up is shown in Fig.4.

5. Results and Discussions

Measurement time step of 0.001 second is used and data are collected for a sample time of 500 seconds (lakhs of data are acquired in such a short span). To exclude the effects of dynamic disturbances like the initial impacts etc., drifting is done whereby the number of data collected is reduced. Average of absolute values of peaks in 10 cutting cycles are considered for each of the force components. The variation of the experimentally obtained milling force components with respect of time for 10 cutting cycles is shown in Fig. 5. The peaks in the graphs denote that cutting forces shoots up quickly to the maximum value when the tool insert starts cutting the workpiece and then reduces rapidly till it exits the work material.
Fig. 5 Variation of the experimentally obtained milling force components with respect of time for 10 cutting cycles

The force profiles with respect to time for developed model are plotted in Fig. 6. The experimental and simulated results of the three force components $F_x$ (along the feed direction), $F_y$ (along the normal direction), and $F_z$ (along the axial direction) at the highest feed rate of 0.09 mm/tooth were compared in the form of a bar graph as shown in Fig. 7. The force evolutions in both cases have acceptable agreement. The maximum error between experimental and developed simulation model’s results for $F_x$, $F_y$ and $F_z$ are 4.1%, 34.7% and 40% respectively.

Fig. 6 Milling force profiles obtained from simulation at a feed rate of 0.09 mm/tooth, doc of 0.8 mm and spindle speed of 202 rpm.
Fig. 7 Comparative bar graph for averages Fx, Fy and Fz values

The effect of feed rate on the cutting force components obtained both from experiment and simulation model is shown in Fig. 8. As feed per tooth increases, forces increase gradually at first and then the increase is at a rapid rate. Increase in feed rate results in increase in cutting thickness which in turn causes an increase in cutting forces.

Fig. 8 Variation of the measured milling force components with respect to feed rate per tooth at a constant depth of cut of 0.8 mm.
6. Conclusions
In this study, a 3D FE model for milling process of DSS 2205 has been developed and a series of experiments for milling of DSS 2205 were carried out to validate the model. The conclusive findings are:

(1) Based on JC material model, a 3D FE model is developed for milling of DSS 2205 and cutting forces are predicted through the model.

(2) The actual geometry of the milling insert was incorporated in the model and the tool was given elastic properties rather than considering it as rigid.

(3) To make the model more realistic, the workpiece was modelled with a pre-machined geometry for the subsequent cutting cycles.

(4) The simulation results show close agreement with the experimental results and the value of feed force was found as maximum followed closely by radial and the force in the axial direction was found to be least in both simulation and experimental results.

(5) The force components increase with respect to increase in feed rate per tooth for both experimental and simulated results.

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