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Multi revolution finite element model to predict machining induced residual stresses in Inconel 718

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Abstract

Inconel 718 is commonly used in structural critical components of aircraft engines due to its mechanical thermal properties at high temperatures, which makes it to be considered as a difficult to machine material. In these critical parts, such as disk turbines, surface integrity should be assured in order to ensure the expected fatigue life. In order to determine the influence of feed and depth of cut in residual stresses a finite element facing model has been developed. This model takes into account the complex thermo mechanical phenomena that take place during chip formation process as well as the effect of cyclic loading phenomena due to the successive revolutions. Firstly, full stress, strain and temperature fields are obtained with a Deform 3D v10.2 nose turning model. Those fields are introduced in a multi revolution Abaqus/Standard v6.12 machining model. Finally the residual stresses of the model are extracted as an approach of Hole Drilling measurement technique. The results are in good agreement with empirical measurements.

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Keywords: Inconel 718; Residual stress; Finite elment method, Turning

1. Introduction

Inconel 718 is commonly used in structural critical components of aircraft engines due to its properties at high temperatures. In order to obtain the final part, these components have to be machined, so the surface integrity after machining becomes a key issue. Residual stresses, which are enclosed among the surface integrity, are an important topic. Although many of the research carried out to study machining induced residual stresses has been empirical, finite element modeling appears to be an alternative solution to study this topic and to gain understanding about it. However, some of the major drawbacks still need to be solved before it will become a reliable tool for industry, such us input parameters identification [1] and computational cost [2].

Considering that machining induced residual stresses are due to non uniform thermal and mechanical loads Torrano *et al.* [3] compared the predictions obtained with AdvantEdge, Deform 3D and Abaqus/Explicit nose turning models with empirical measurements. They concluded that Finite element modeling can provide qualitative information about residual stresses. However, the computational cost was very high and in consequence only few milliseconds were simulated.

In order to reduce computational cost, Salio *et al.* [4] simplified a nose turning problem in a 2D orthogonal cutting model. Umbrello *et al.* [5] developed and hybrid methodology combining finite element method and artificial neural network. Valiorgue *et al.* [6] proposed and hybrid methodology combining empirical machining forces with finite element modeling. In the initial step several empirical machining tests were conducted to obtain cutting forces. Then, with an open tribometer, the tool-workpiece contact law was characterized. Using analytical approaches, the mechanical and thermal loads to introduce in a simplified machining model were defined. Finally, loads were applied in a finite element model avoiding the chip formation process. Mondelin *et al.* [7] adapted the hybrid methodology to the peculiarities of 3D machining showing that, at least 5 revolutions are necessary in order to obtain a stationary residual stress profile.

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In this research a finite element model is proposed in order to better reproduce residual stress generation process. Firstly, full stress, strain and temperature fields are obtained with a Deform 3D v10.2 nose turning model. Then, those fields are introduced in a multi revolution Abaqus/Standard v6.12 machining model. Finally the results are extracted as an approach of Hole Drilling technique and compared with empirical measurements.

2. Geometrical analysis

Nose turning has some geometrical peculiarities. The first peculiarity, as shown in figure 1, is that in contrast to orthogonal cutting, each revolution contributes in the final surface generation. So with each revolution, the final surface increases in a distance equal to the feed (*f*). The second peculiarity is that the uncut chip thickness along the tool workpiece contact zone is not constant. In the scheme presented in figure 1 can be seen that the vertical projection of the uncut chip thickness (h_1) varies considerably, being 0 in the beginnings of the final surface and a value depending on tool radius (*R*), feed (*f*) and depth of cut (*d.o.c*). Figure 2 shows the evolution of h_1 along the tool-workpiece contact length (l_{mec}).

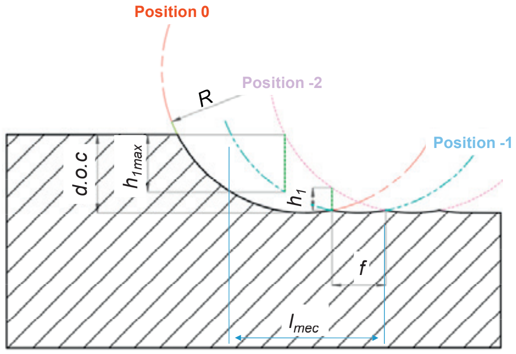

Figure 1. Nose turning geometrical scheme.

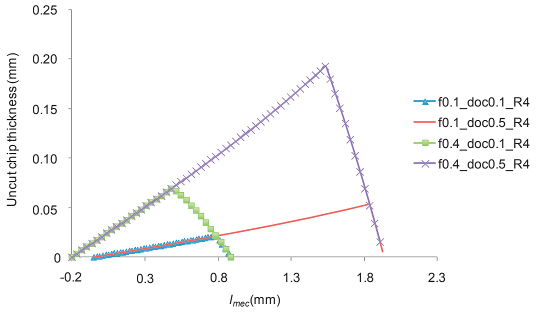

Figure 2. Uncut chip thickness along tool workpiece contact length.

Therefore, it is observed that the final surface (i) is obtained removing a few micros uncut chip thickness and (ii) that the material in the final surface has suffered several cycles of mechanical and thermal loads. For example, as shown in table 1, for a 4 mm tool radius, 0.1 mm feed and 0.5 mm depth of cut, a final surface material point has to withstand approximately 20 cycles.

Table 1. Number of loading cycles that has to withstand a final surface material point.

f (mm)	*d.o.c* (mm)	R (mm)	l_{mec} (mm)	n_{cycle}
0.1	0.1	4	0.9	9
0.1	0.5	4	1.95	20
0.4	0.1	4	1.1	3
0.4	0.5	4	2.2	6

3. Methodology

In this research a facing multi revolution finite element model has been developed. In order to validate the model and show its capabilities several tests have been done. Firstly, based on the DOE methodology an Inconel 718 disc has been machined using 4 different cutting conditions (table 2). Machining forces have been measured. In test 1 and 3 surface residual stresses have been measured using the hole drilling technique. In order to approach as much as possible to the cutting conditions used in the industry, as shown in table 3, 4 millimeter nose radius tool insert has been used. Then, the simulations with the nose turning model have been conducted. To validate the model, machining forces have been compared with empirical measurements. Finally, using the multi revolution model the tests 1 and 3 have been conducted. In these tests residual stresses have been extracted and compared with empirical ones.

Table 2. Cutting conditions

	V_c (m·min^{-1})	*f* (mm·rev^{-1})	*doc* (mm)	*Maximum uncut chip thickness (mm)*
Test 1	30	0.1	0.1	0.021
Test 2	30	0.1	0.5	0.053
Test 3	30	0.4	0.1	0.069
Test 4	30	0.4	0.5	0.192

Table 3. Tool geometry.

	Value
Cutting edge radius (*rh*) (μm)	40
Nose radius (*R*) (mm)	4
Rake angle (º)	0
Inclination angle (º)	0
Clearance angle (º)	7
Tool Material	ISO S1

4. EXPERIMENTAL SET UP

A vertical CNC lathe equipped with a special designed fixture system to avoid bending has been used to machine Inconel 718 laminated discs. To measure machining forces (see figure 3) a Kistler 9121 dynamometer has been used. Finally, residual stresses have been measured with hole drilling technique. 0.98 mm hole diameter has been used.

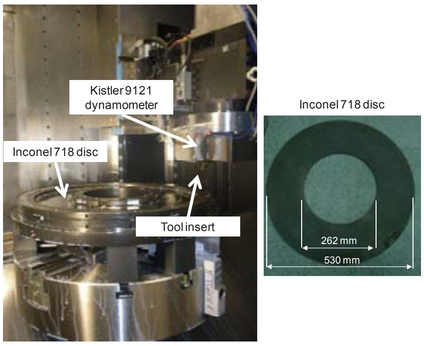

Figure 3. Experimental set up.

5. FINITE ELEMENT MODEL

The solution proposed in this research is composed by a (i) Deform 3D nose turning model and a (ii) multi revolution Abaqus/Standar model, based on the hybrid model developed by Mondelin *et al.* [7]. As shown in figure 4, a nose turning model has been use to obtain the final surface temperature, stress and strain fields, during chip formation process. Then the stress fields are mapped in a multi revolution model. In order to simulate tool movement, the model has several steps. In each step, the temperature, stress and strain fields are positioned with the tool position and mapped in the model. Then a short relaxation starts to equilibrate fields. During the relaxation, tool advances, so the fields are positioned and mapped again. Once a revolution has been finished, a big relaxation starts. Its duration is equal to the tine that needs the tool to perform a revolution. The process continues until it reaches the desired number of revolutions.

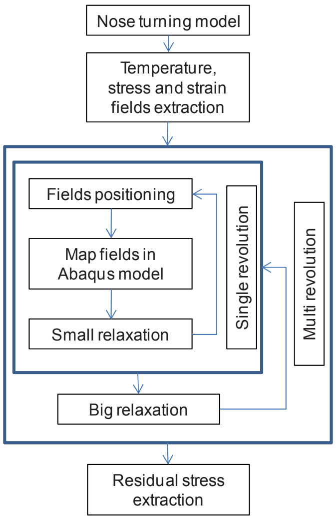

Figure 4. Proposed solution diagram.

5.1. Nose turning model

A lagrangian quasi static implicit Deform 3D nose turning model has been used (figure 5). The tool has the cutting movement and in all free surfaces the heat exchange with the environment is allowed. In order to reproduce the effect of the uncut chip thickness the optimum element size would be 1 µm, but due to computational limitation a 10 µm minimum element size has been chosen. Bigger mesh size can vary the geometry of the problem and in consequence thermal and mechanical loads. All simulations have been carried out until 1.5 cutting length.

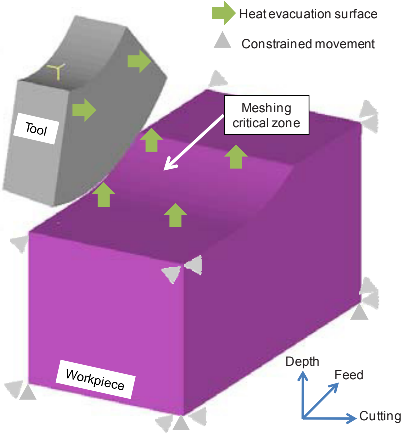

Figure 5. Nose turning model.

5.2. Temperature, stress and strain field extraction

Once the nose turning simulations has been finished, temperature, stress and strain fields have been extracted. To better reproduce the complex thermo-mechanical phenomena that happen during machining the data extraction zone is close to the chip. As shown in figure 6, the upper limit matches with the final surface and the feed direction length is equal to the tool workpiece contact length (l_{mec}).

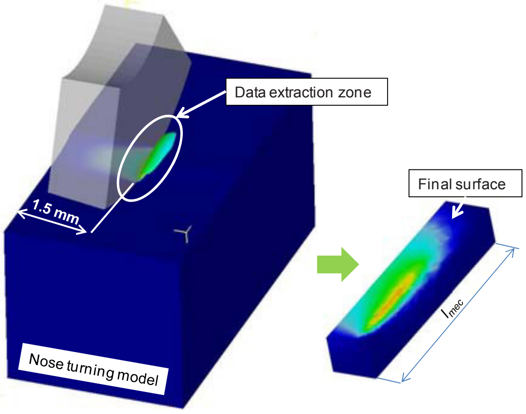

Figure 6: Data extraction procedure

5.3. Multi revolution model

As shown in figure 7, in order to reduce computational cost only a small portion of the final surface has been analyzed in the multi revolution model, 6 mm in feed direction, 3 mm in cutting direction and 1 mm in depth direction. Near 200,000 brick elements have been used with a minimum element depth of 10 µm in order to reproduce temperature strain and stress gradients in depth direction. The displacement of all exterior surfaces except the top, have been restricted. In the top surface, final surface, a heat convection boundary condition has been imposed.

The model consists in several Abaqus Standard static relaxation simulations. In each simulation the data extracted from the nose turning model is mapped using self made software. This software extracts the previous simulation results and adds the data extracted from the nose turning model, which moves joint to the tool as shown in figure 7. In the adding process the temperatures strain and stress of the elements inside the working zone (figure 7) have been replaced with those obtained from the nose turning model. In order to guaranty the results quality, the duration of each simulation depends on the minimum element size and cutting speed. So that the tool does not advance more than an element in each simulation.

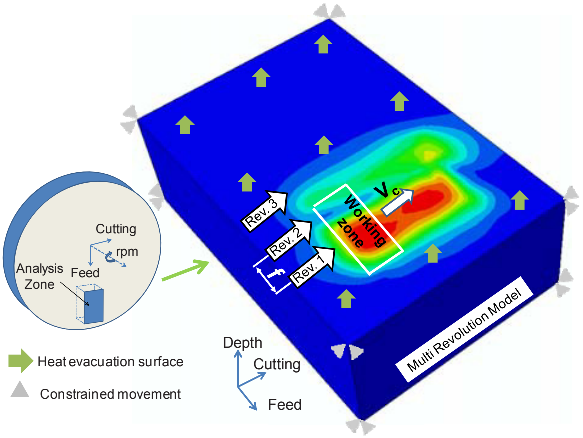

Figure 7. Multi revolution model.

Once a revolution has been finished, a relaxation step starts. The duration of this relaxation step is equal to the time needed by the tool to make a revolution. In this case for a diameter of 300 mm and a cutting speed of 30 m·min^{-1}, the duration is close to 1.8 s

5.4. Material and contact input data

The input data for Inconel 718 used in nose turning and multi revolution models is the same us that used by authors in previous work [3]. A 0.23 constant coulomb friction coefficient has been used [4]. The Johnson Cook constitutive model has been defined using the data proposed by Mitrofanov *et al*. [8].

6. Results and discussion

6.1. Machining forces

The predicted and measured machining forces show that the maximum uncut chip thickness is an important parameter in cutting and passive forces. As shown in figure 8, even if, with small values the trend is not clear, an increase of the maximum uncut chip thickness entails bigger forces. In feed forces case, the trend is not clear.

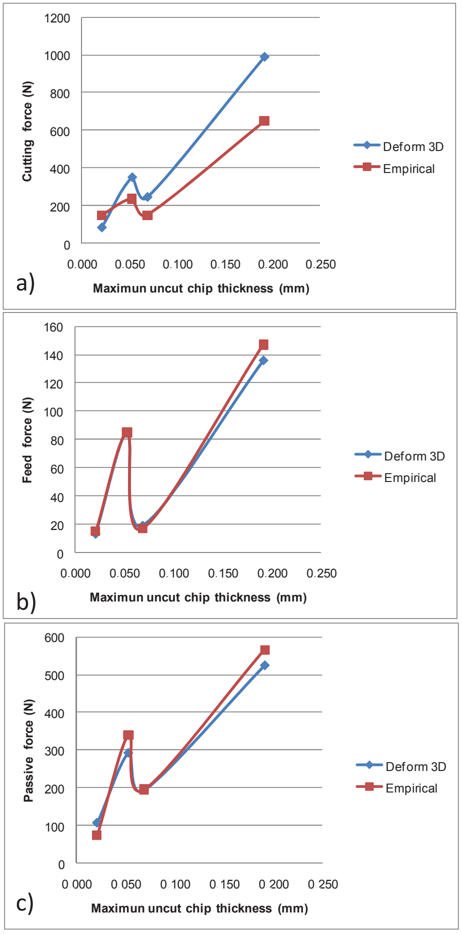

Figure 8. Predicted and measured machining forces: a) cutting force, b) feed force and c) passive force.

The predicted feed and passive forces are close to measured ones, with a maximum difference of 7% in both cases. However the difference in cutting forces is considerably greater, close to 50% in the case of bigger maximum uncut chip thickness. In general, predicted cutting forces are bigger than measured ones, maybe because the material constitutive law is too stiff.

6.2. Residual stresses

Before start analyzing residual stresses some considerations has been done about nose turning model. The first one is that the maximum uncut chip thickness in the final surface for a feed of 0.1 is close to 1.5 µm while for a feed of 0.4 is 40 µm. This minds that the minimum element size is 7 times bigger in the worst case. The second one is that, as mentioned before, the used material constitutive law is to stiff.

Despite the drawbacks, in table 4 the surface predictions obtained with the nose turning model, multi revolution model and hole drilling measurements have been summarized. Considerable differences have been observed in test 1, while in test 3 the multi revolution model predictions are close to empirical measurements. The results show that 10 µm element size is not enough to represent the thermo-mechanical phenomena that take place when machining test 1. It seems that due to bad contact between the tool and workpiece, the final surface has been less heated.

Table 4. Average surface residual stresses.

Technique	Test 1		Test 3	
	Cutting stress (MPa)	Feed stress (MPa)	Cutting stress (MPa)	Feed stress (MPa)
Hole drilling	703	181	1249	631
Nose turning model with relaxation	130	-106	104	529
Multi revolution model	148	-50	1290	660

In the test 3 the maximum uncut chip thickness in the final surface is close to 40 µm, 4 times bigger than the minimum element size. This ratio seems enough to reproduce the phenomena that take place during machining. However the nose turning model results are far from the experimental ones. As shown in figure 9, the residual stress distribution, predicted by the nose turning model, along the final surface is not homogenous. Considerable variations have been observed in cutting direction. Near the chip stresses are very tractive, close to 900 MPa and near the free surface the stresses are very compressive, close to 60 MPa. It seems that even the forces and temperatures have obtained a steady state, this not happens with residual stresses.

The multi revolution model residual stress predictions are close to empirical ones, 1290 MPa vs. 1249 MPa. As shown in figure 10 a homogeneous stress field has been obtained in cutting direction and in feed direction, the stresses of the final surfaces goes from 1030 MPa to 1550 MPa, so it seems that uncut chip thickness may be an important parameter in order to analyze residual stresses. In the zones machined with bigger uncut chip thickness, more tractive residual stresses have been obtained.

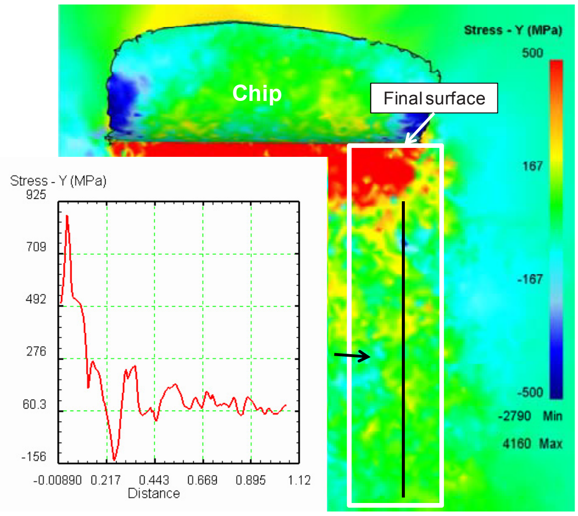

Figure 9. Cutting direction stresses for test 3 obtained by nose turning model.

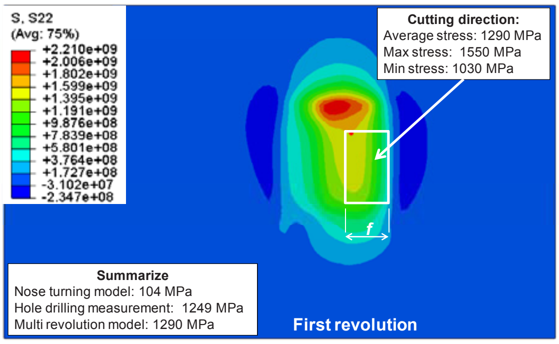

Figure 10 Multi revolution model cutting direction residual stress predictions for test 3.

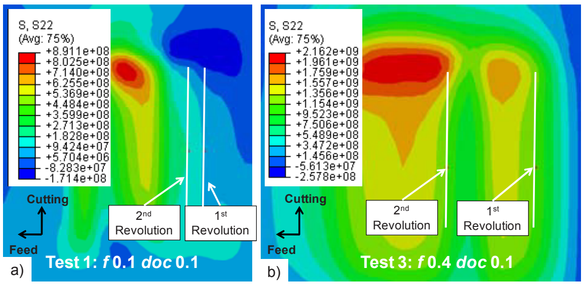

Figure 11: Multi revolution model cutting direction residual stress predictions for a) test 1 and b) test 3.

As shown in figure 11, the multi revolution model shows that feed has influence in the stress field distribution. With 0.1 mm feed homogeneous surface residual stress distribution has been obtained in the final surface. However, with 0.4 feed heterogeneous stress field has been obtained. In both cases, during the second revolution, in the final surface close to the beginning of the second revolution the residual stresses become less tractive. This could be due to the gentle warning that occurs in this zone.

In test 3, with the multi revolution model, after three revolutions enough space has been obtain in order to reproduce hole drilling measurement technique (see figure 12). In cutting direction 1160 MPa average value and 245 MPa standard deviation has been obtained. In the feed direction the residual stresses have been significantly reduce from the first revolution, 660 MPa *vs* 287 MPa. Therefore boundary conditions and mapping system should be checked in order to obtain better predictions.

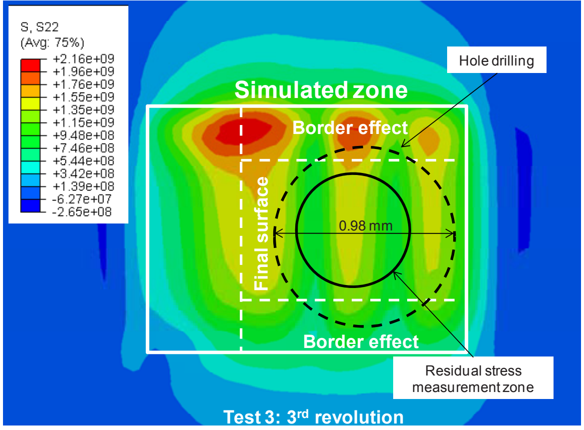

Figure 12: Multi revolution model cutting direction residual stress after the 3rd revolution.

7. Conclusion

In this study a multi revolution residual stress prediction model for Inconel 718 nose turning has been presented. In the model validation process the following conclusions have been obtained:

- Increasing the maximum uncut chip thickness the cutting and passive forces increase. The feed force does not follow the same trend.
- The minimum element size of the nose turning model should be smaller than the maximum uncut chip thickness in the final surface in order to reproduce the thermo-mechanical loads generated during machining.
- Temperature and forces steady state does not mean residual stresses steady state. With the Multi revolution model steady state can be obtain faster.
- The multi revolution model provides information of the effect of successive revolutions in the final surface residual stress distribution.
- Compare to the nose turning models, with multi revolution model it is possible to obtain enough simulated space to reproduce hole drilling technique.

8. Acknowledgements

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