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3D residual stress modeling in turning of AISI 4140 steel

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1. INTRODUCTION

It is well known that residual stress generated in the surface by turning process strongly affects its fatigue strength [1]. In particular, axial turning process of round bars is widely in practice in automobile and aerospace industry. Thus, there are high demands to predict residual stress accurately in the turned surface. Lots of modeling efforts have been made to simulate and predict residual stress in axial turning process. Extensive review on these modeling efforts was done by Elsheikh et al. [2]. 2D numerical Lagrangian modeling has been employed, but it involves some mesh distort issues [3]. 2D Arbitrary Lagrangian Eulerian (ALE) formulation can improve these mesh distort issues [4]. However, there is still limit to model residual stress in the actual 3D axial turning process in industry. To meet requirements to simulate 3D axial turning process in industry, 3D Lagrangian modeling softwares, such as DEFORM 3D, have been employed. This 3D modeling has an advantage to model and import complicated tool insert geometries, such as chamfer and predict residual stress in the turned surface decently [5]. However, this 3D Lagrangian modeling software always involves chip formation, which requires long computation time.

Valiorgue et al. [6] showed that it needs at least five revolutions to reach steady states in residual stress during axial turning process. Therefore, it is necessary to take into consideration of these multi-revolutions in residual stress modeling during turning. However, current chip separation approaches in 3D Lagrangian modeling of turning have difficulties in integrating this multi-revolution process due to long computation time. To overcome these difficulties, they [6] have applied equivalent thermo-mechanical loadings on the machined surface in five paths without chip formation and obtained good agreement with experimental residual stress. Mondelin et al. [7] also showed good agreement in residual stress prediction in turning of 15-5PH with this type of hybrid model.

The machined surface forms a shape of “cylindrical groove”, which is generated by tool tip radius and machining parameters, such as feed and depth of cut. Therefore, Dumas et al. [8] modeled the physical shape of the turned surface and applied 3D equivalent thermo-mechanical loadings. They improved residual stress prediction especially in the cutting directions. Recently, this hybrid model has been integrated into a server based software, which is called as MISULAB.

Extensive modeling efforts of residual stress were seen in materials, such as AISI 52100, AISI 316L, IN 718, Ti-6Al-4V [9]. On the other hand, in spite of wide industrial adoption of AISI 4140 steel, a few 3D modeling of residual stress was attempted [10]. Therefore, this study presents simulation procedure and validation of residual stress gradient in turning of AISI 4140 steel with MISULAB simulation.

2. MATERIAL AND METHODS

2.1. Material and experimental setup

AISI 4140 steel (also known as 42CrMo4) is adopted as a material due to its high demand in the industry. Experimental setup for turning of AISI 4140 steel is shown in Figure 1. An AISI 4140 bar having a diameter of 44 mm and a surface hardness of 35 HRC was installed in the CNC turning machine (CMZ TC25Y). A dynamometer (Kistler 9257A) was installed to measure experimental cutting forces during turning. Tool insert (CCMT120404-RP4 WPP20S) and tool holder (SCLCR2020K12) was used. Corresponding tool geometry is summarized in Table 1. As a reference condition, turning was performed with cutting speed of $V_c = 200$ m/min, feed of $f = 0.1$ mm/rev, depth of cut of $a_p = 0.2$ mm, and cutting length of $L = 20$ mm. No lubrication was used. The machined surfaces were analyzed with X-ray diffraction (XRD) method to obtain residual stress profile. An XRD

equipment (Proto) was used. Detailed XRD measurement parameters are given in Table 2.

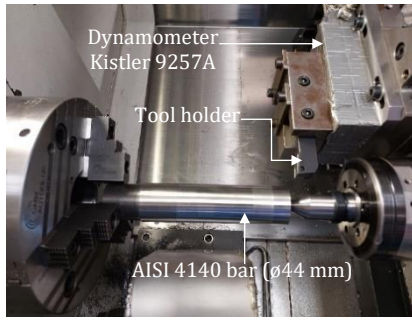


Figure 1 – Experimental setup for turning of AISI 4140 steel.

Table 1 – Tool geometry.

Parameter	Value
Edge length (mm)	12
Edge sharpness radius (mm)	0.06
Insert angle (°)	80
Insert tip radius (mm)	0.4

Table 2 – XRD measurement parameters to analyze residual stress gradients in AISI 4140 machined surface.

Parameter	Value
Diffraction condition	Cr K α radiation with 18 kV, 4 mA
Wavelength	$\lambda = 2.291$ nm
-S1 (v/E)	1.237×10^{-3} GPa $^{-1}$
S2/2 (1+v)/E	5.709×10^{-3} GPa $^{-1}$
Plan {h k l}	{ 2 1 1 }
Bragg's angle	$2\theta = 156.08^\circ$
Beam size	$\phi 2$ mm
Polishing strategy	Electropolishing process

3. SIMULATION WORKS

After finishing all experimental works, 3D modeling simulation with a commercial software, MISULAB was conducted. Detailed procedure of the simulation is described in the article published by Dumas et al. [8]. MISULAB simulation consists of six steps as shown in Figure 2. For simulation works, all thermophysical properties [11] of AISI 4140 steel are given in Table 3. As a constitutive law of the workpiece material, Johnson-Cook (JC) model is employed and its coefficients is given in Table 4. Carbide tool was used in this study. Thus, values of tool material properties and friction coefficients between workpiece and tool surfaces are given in the study of Dumas et al. [8].

In the first step (called as step 1) of MISULAB in Figure 2, considering cut sections (CS), series of 2D orthogonal cut sections having a local uncut chip thickness of $h = 0.01, 0.03, 0.05, 0.07,$ and 0.09 mm were chosen. In the second step (step 2), in order to obtain 2D equivalent loading, ABAQUS simulation was conducted. 2D CEL orthogonal cutting simulation, which is developed by Aridhi et al. [12] is used. Its geometry and boundary condition are explained in detail in their study. As thermo-mechanical loadings, heat flux density, HFL (W/mm 2), tangential

pressure, S12 (MPa), and normal pressure, S22 (MPa) were calculated. One example of extractions of thermo-mechanical loadings (HFL, S22, S12) with $h = 0.05$ mm and their approximations are shown in Figure 3. In the third step (step 3), numerical cutting force, $F_{Y-TOT(NUM)}$, and penetration force, $F_{Z-TOT(NUM)}$, are calculated in ABAQUS.

Table 3 – Thermophysical properties of AISI 4140 steel [12].

Parameter	Temperature (°C)	Value
Thermal conductivity (W/m/°C)	20	43.6
	200	41.7
	400	38.0
	600	32.8
Specific heat (J/kg/°C)	20	437
	200	477
	400	523
	600	568
Density (Kg / m 3)	20	7844
	1000	7434
Young's modulus (MPa)	20	212000
	1200	137530
Thermal expansion coefficient (/°C)	0	0
	20	0
	23	0.00001120
	700	0.00001460
Poisson's coefficient ()	-	0.289

Table 4 – Johnson-Cook model parameters for AISI 4140 steel [12].

A (MPa)	B (MPa)	n	C	ϵ_0	m	T_m (°C)	T_0 (°C)
598	768	0.209	0.0137	1	0.807	1520	25

In the next step (step 4), approximated 3D equivalent loadings can be applied to the round machined surfaces. However, these thermo-mechanical loadings require a calibration step to compensate for its inaccurate estimation from 2D calculation. Therefore, the fifth step (step 5) provides this compensation process. Since experimental cutting force, $F_{Y(EXP)}$, penetration force, $F_{Z(EXP)}$, were measured in section 2, their ratios, such as G_{FY} and G_{FZ} , can be defined in equation (1) and given in Table 5. HFL and S12 are multiplied by G_{FY} and S22 is multiplied by G_{FZ} . Thus, calibrated 3D equivalent loadings can be obtained. Its element and mesh size are given in Table 6. The final step (step 6) can be performed in the solver, SYSWELD. The 3D equivalent loadings can be applied to the 3D finite element in Figure 4. Eight revolutions were simulated in SYSWELD

$$G_{FY} = \frac{F_{Y(EXP)}}{F_{Y-TOT(NUM)}}, \quad G_{FZ} = \frac{F_{Z(EXP)}}{F_{Z-TOT(NUM)}} \quad (1)$$

Table 5 – G_{FY} and G_{FZ} values.

Parameter	Value	Parameter	Value
$F_{Y(EXP)}$ (N)	69	$F_{Z(EXP)}$ (N)	63
$F_{Y-TOT(NUM)}$ (N)	75	$F_{Z-TOT(NUM)}$ (N)	91
G_{FY}	0.91	G_{FZ}	0.69

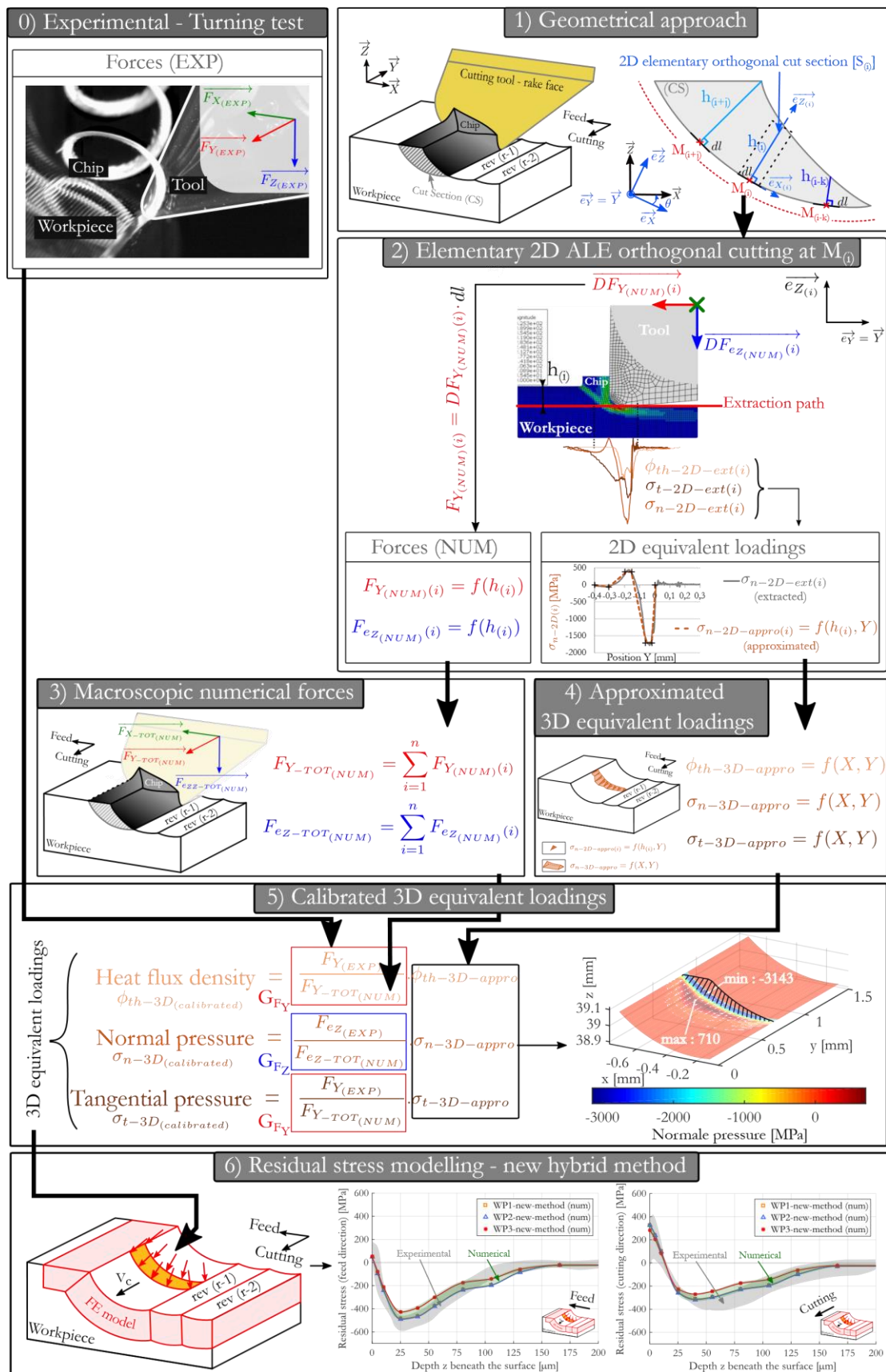


Figure 2 - Schematic diagram of MISULAB simulation (Dumas et al. [8]).

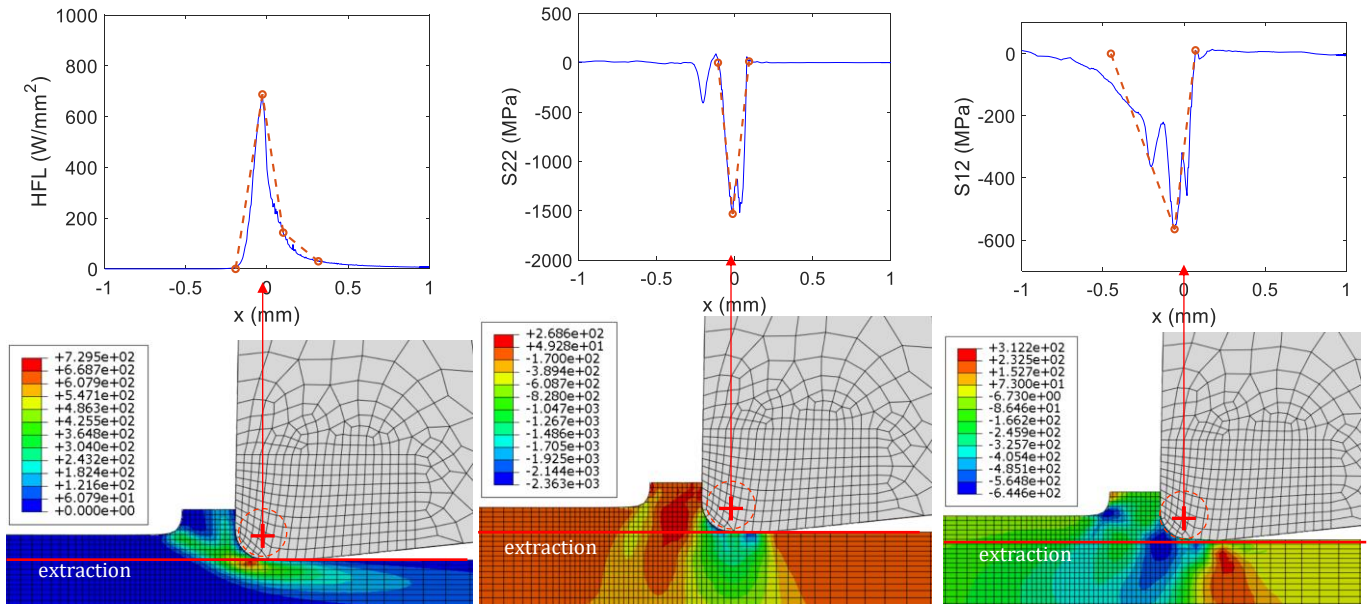


Figure 3 – Extractions of thermo-mechanical loadings (HFL, S22, S12) with $h = 0.05$ mm and their approximations.

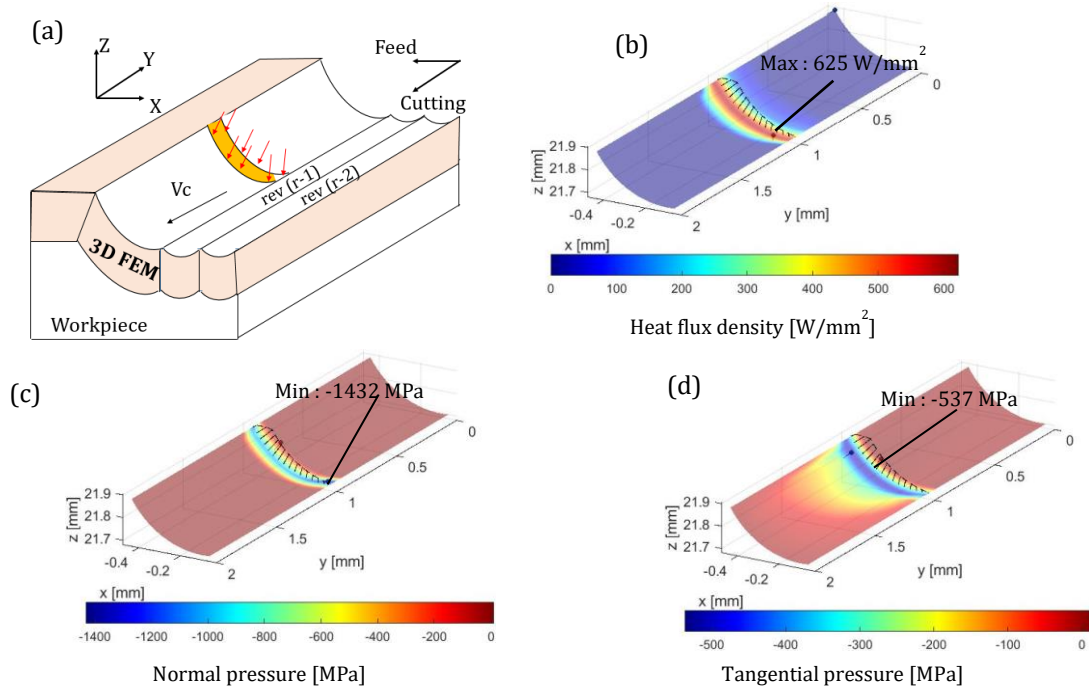


Figure 4 – (a) 3D finite element model, (b) HFL, (c) S22, (d) S12.

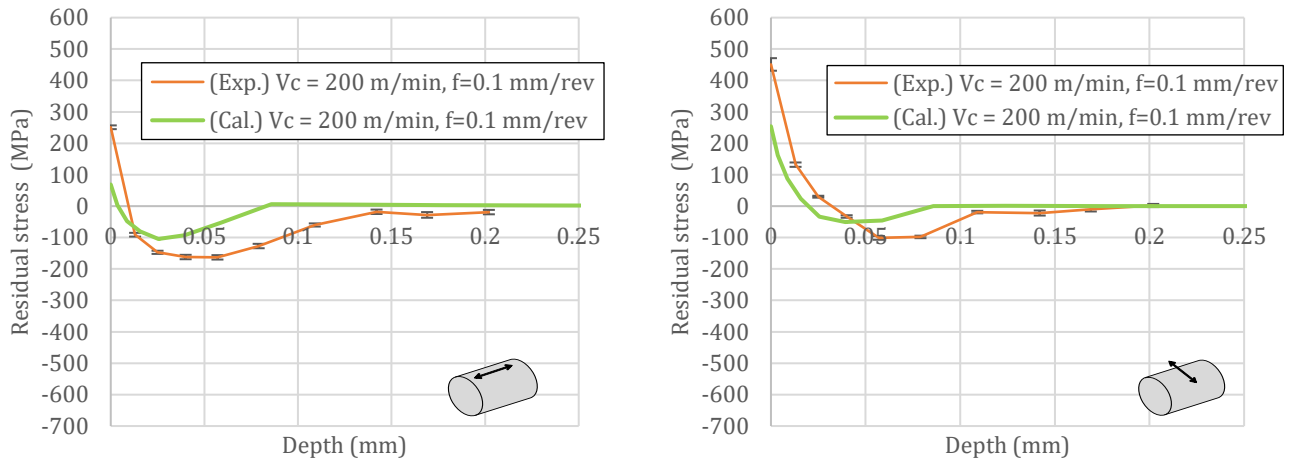


Figure 5 – Experimental and numerical residual stress profiles in turning of AISI 4140 steel: (a) feed, (b) cutting directions.

Table 6 – Elements and mesh size for AISI 4140 turning simulation in SYSWELD (Code is stated in [8]).

Code	Parameter	Value
L _a	AFTER element length (mm)	0.03
L _s	CURRENT element length (mm)	0.03
L _b	BEFORE element length (mm)	0.09
T _s	Element thickness (mm)	0.01
T	Mesh thickness (mm)	2
D _s	Finite element depth (mm)	0.003
D1	Upper depth (mm)	0.25
D	Total depth (mm)	1
B _{d1}	Upper bias	1.4
B _{d2}	Lower bias	1.6

After conducting SYSWELD calculation, residual stress gradients in the machined surface and sub-surface can be obtained. In Figure 5, measured (exp.) and calculated (cal.) residual stress are compared. Good agreement between measured and calculated residual stress gradients are seen thanks to hybrid model approach. Surface stress and affected depth in residual stress profile can be predicted more accurately by applying more precise equivalent thermomechanical loadings. Such improvement in calculation of equivalent thermomechanical loadings can be done by incorporating more accurate tool geometry, such as flank wear length in ABAQUS in the second step (step 2) in MISULAB simulation. This improvement process is underway.

4. CONCLUSION

This study deals with 3D residual stress modeling procedure and validation in turning of AISI 4140 steel with MISULAB. It is shown that this MISULAB simulation is capable of predicting residual stress profiles in turning of AISI 4140 steel. Corresponding information, such as tool geometries, material properties, thermo-mechanical loadings, experimental cutting and penetration forces are saved in the server based software, MISULAB. Thus, relevant industries can use this database in their residual stress prediction promptly. Further case studies with different cutting parameters, such as feed, and tool geometries, such as tool flank wear length, can be carried out.

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