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PREDICTIVE MODELLING OF THE RESIDUAL STRESSES DISTRIBUTION IN THE AIRCRAFT STEEL PART AFTER MACHINING

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ABSTRACT

In machining of parts for the aircraft industry, residual stresses are ones of the most specified customer requirements. This paper utilizes modelling analysis to predict residual stresses values for variety of cutting conditions in finish turning of the aircraft steel AISI 9310. Taguchi method and ANOVA analysis were used to determine if the independent variables like flank wear VB and feed *f* are related to the components of the residual stresses, and to explore the forms of these relationships.

Keywords: residual stresses, aircraft steel, Taguchi method, ANOVA analysis

1. INTRODUCTION

Manufactured components products are expected to demonstrate superior quality and enhanced functional performance [1-3]. Material removal processes like turning, milling and grinding dominate among all manufacturing processes. Significant efforts were made by numerous investigators in the past few decades to investigate the nature of the surface alterations produced by the various material removal processes and to correlate them with the product’s functional performance [1-5]. In machining of parts for the aircraft industry, residual stresses are ones of the most specified customer requirements. Numerous studies show that the main causes of this phenomenon include formation of internal stresses at the stage of initial technological processes of the forming of semi manufactured parts, i.e. metallurgical processes, cutting, plastic processing, heat processing etc. [3-6].These stresses results from the changes in energy. They lead to the formation of material fatigue damages. The fatigue is significantly affected by several parameters such as surface roughness, residual stresses and microstructure, which are commonly summarized by the term ‘surface integrity [4]. Surface integrity depends on the thermo-mechanical loadings induced by all the previous manufacturing operations [7]. Aircraft steel AISI 9310 is a nickel – chrome – molybdenum case-hardening steel, with good strength and toughness properties. It shows high hardenability, high core hardness and high fatigue strength [8]. This paper focuses of the modeling of cutting process and predicts the residual stresses values for variety of cutting conditions in finish turning of the aircraft steel AISI 9310.

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2. MODELLING

The experiments were conducted using aircraft steel alloy AISI 9310 with hardness 255 Bhn as a workpiece material and carbide insert as a tool. The chemical composition of the steel is shown in Table 1. The research plan was developed by Taguchi method [9] for the two variables: feed (*f*) and wear (flank wear VB connected with fillet radius), assuming four levels.

Table 1
Composition of aircraft steel AISI 9310

Material	C	Cr	Mn	Mo	Ni	P, S	Si
AISI 9310	0.08	1.2	0.55	0.12	3.25	0.025	0.28

Cutting speed was constant, $v_c = 122$ m/min. Cutting data are shown in Table 2. According to the Taguchi quality design concept a L16 orthogonal array has been used to determine the S/N ratio, ANOVA and 'F' test values for indicating the most significant parameters affecting the machining performance criteria, in our case - residual stresses. To obtain optimal testing set of cutting data, the-lower-the-better quality (1) characteristic was accepted.

$$\frac{S}{N} = -10 \cdot \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Table 2
Cutting data

Symbol	Cutting data	Level			
A	Feed f [mm/rev]	0.035	0.060	0.085	0.110
B	Flank wear VB / fillet radius r_n [mm]	0/0.03	0.1/0.05	0.2/0.07	0.37/0.09

The three-dimensional Lagrangian finite element method [10] was applied for the numerical computations. Techniques such as adaptive remeshing and thermal analysis was integrated to model the complex interactions of the milling tool wedge and work-piece material. The constitutive model by which the material is governed is shown in Equation (2). The geometry of tool and direction of residual stresses components are presented in fig.1.

$$\sigma(\varepsilon^p, \dot{\varepsilon}, T) = g(\varepsilon^p) \times \Gamma(\dot{\varepsilon}) \times \Theta(T) \tag{2}$$

where $g(\varepsilon^p)$ is strain hardening, $\Gamma(\dot{\varepsilon})$ is strain rate sensitivity and $\Theta(T)$ is thermal softening.

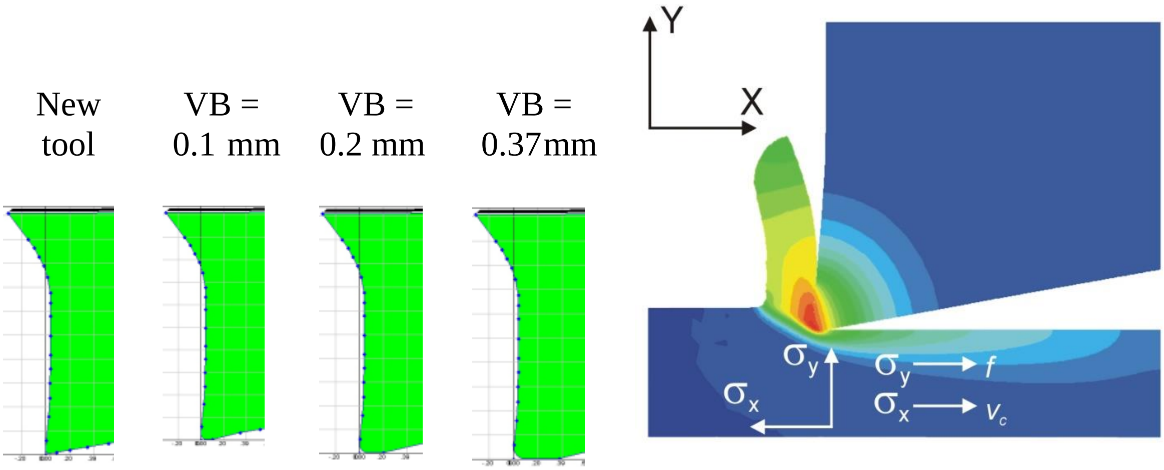

Fig. 1.
Tool geometry applied in the simulation modeling (left) and cutting zone (right)

The results of numerical calculations of the residual stresses component σ_{xx} (in cutting speed direction) are presented in Table 3. Distributions of temperature (in tool) and stress σ_{xx} (in upper layer of the workpiece) for different flank wear are presented in fig. 2 (for feed f=0.11 mm) and fig. 3 (for feed f=0.035 mm).

The analysis shows that the optimal cutting data for achieving the best solution are data from the test number 2, (f = 0.06 mm/rev, VB = 0 mm) for which S/N factor has the lowest value.

Table 3
Results of FEM calculations and S/N ratio

No	**A**	**B**	**VB**	***f***	**σ_{xx}**	**S/N**
1	1	1	0	0.035	90.0	-39.1
2	1	2	0	0.06	61.7	-35.8
3	1	3	0	0.085	76.7	-37.8
4	1	4	0	0.11	96.7	-40.3
5	2	1	0.1	0.035	161.0	-44.6
6	2	2	0.1	0.06	166.0	-44.7
7	2	3	0.1	0.085	230.0	-47.3
8	2	4	0.1	0.11	157.7	-44.0
9	3	1	0.2	0.035	158.0	-44.7
10	3	2	0.2	0.06	261.7	-48.7
11	3	3	0.2	0.085	337.7	-51.0
12	3	4	0.2	0.11	341.7	-50.7
13	4	1	0.37	0.035	162.7	-44.6
14	4	2	0.37	0.06	277.7	-48.9
15	4	3	0.37	0.085	341.0	-50.7
16	4	4	0.37	0.11	370.0	-51.4

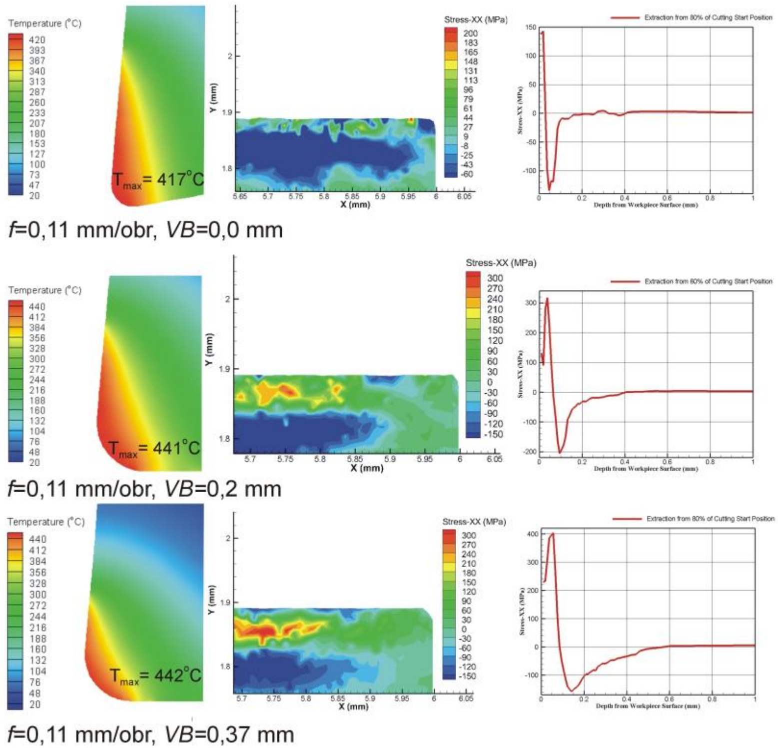

Fig. 2.

Distributions of temperature (in tool) and stress σ_{xx} (in upper layer of the workpiece) for feed *f*=0.11 mm and different flank wear

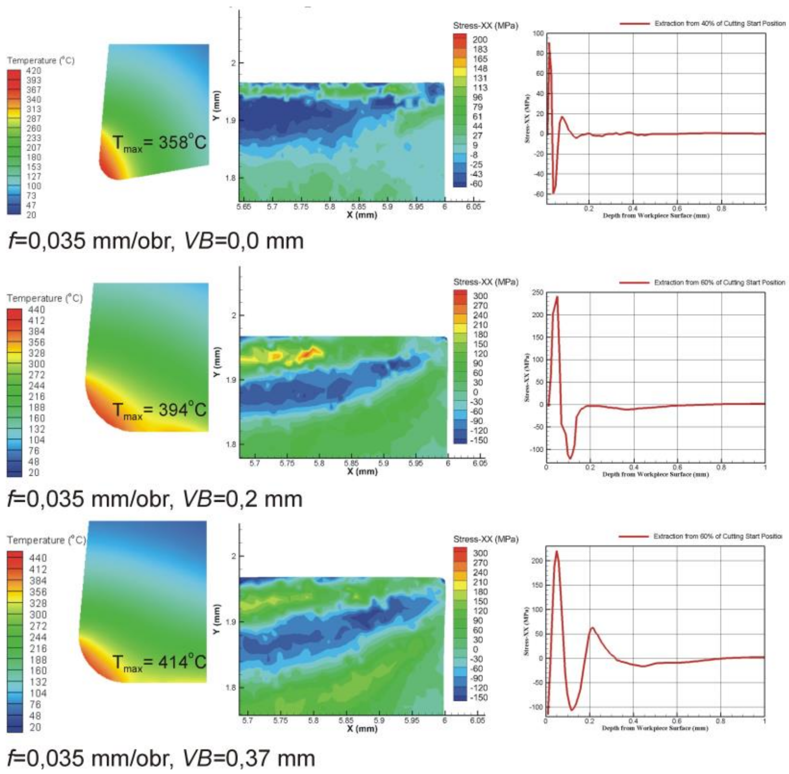

Fig. 3.

Distributions of temperature (in tool) and stress σ_{xx} (in upper layer of the workpiece) for feed *f*=0.035 mm and different flank wear

3. ANALYSIS OF VARIANCE

Figure 4 and table 4 present the ANOVA analysis results for residual stresses existing in the upper layer of the aircraft steel workpiece and polynomial regression function.

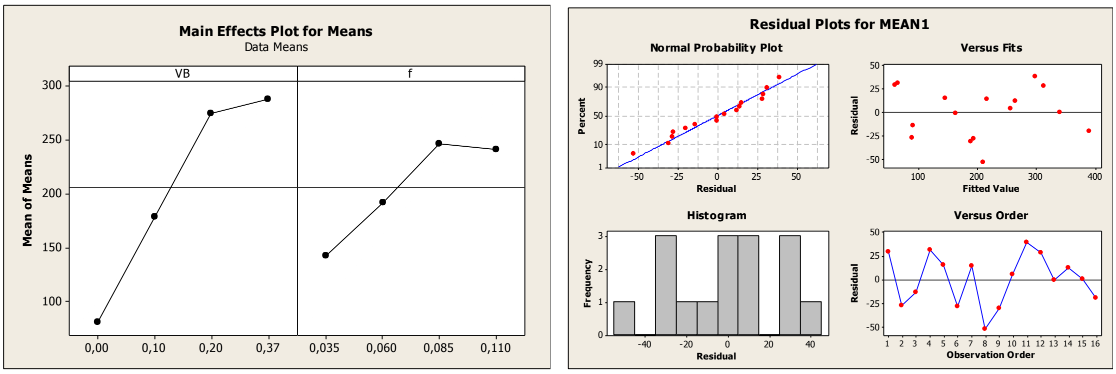

Fig. 4
Graphic representation of the effect of variables (flank wear VB and feed *f*) on mean value (a) and residual plots for mean (b)

Table 4
Analysis of variance for stress values in machining of aircraft steel

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	5	152127	152127	30425.4	28.55	0.000
Linear	2	117006	127905	63952.7	60.01	0.000
VB	1	92459	98678	98677.6	92.60	0.000
f	1	24547	29228	29227.7	27.43	0.000
Square	2	20126	20126	10063.1	9.44	0.005
VB*VB	1	17246	17246	17246.2	16.18	0.002
f*f	1	2880	2880	2880.1	2.70	0.131
Interaction	1	14995	14995	14995.1	14.07	0.004
VB*f	1	14995	14995	14995.1	14.07	0.004
Residual Error	10	10656	10656	1065.6		
Total	15	162783				

Estimated Regression stress function using data in uncoded units is shown in Equation (3).

$$\sigma_{xx} = \mathrm{f}(VB, f) = -23{,}84 + 784{,}81 \cdot VB + 3171{,}31 \cdot f - 2132{,}78 \cdot VB^2 - 21466{,}7 \cdot f^2 + 8016{,}07 \cdot VB \cdot f \qquad (3)$$

$R^2 = 0.85$

4. CONCLUSIONS

Based on the analysis, the following conclusions can be made:

- The Taguchi method, used to optimize the turning process of aircraft steel because of the residual stresses values occurring in the surface layer of the workpiece can be an effective method. This is confirmed by the calculated values of the parameter R^2 obtained by ANOVA analysis.

- The ANOVA analysis presents that the value of wear of the cutting tool (described by the parameter VB) has a significant impact on the stress in the surface layer of the workpiece. The feed parameter has a lesser impact on the stress value. The most optimal way to minimize the stresses in the surface layer of the workpiece is a usage of the new tool (or the tool with a flank wear parameter VB <0.1 mm) and low values of the feed.
- An adoption of a polynomial function of the model gives an enough good fit for that case.
- In the case of the cutting parameters optimization the mathematical models should be experimentally verified.

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5. REFERENCES

[1] I.S. Jawahir, E. Brinksmeier, R.M. Saoubi, D.K. Aspinwall, J.C. Outeiro, D. Meyer, D. Umbrello, A.D. Jayal, Surface integrity in material removal processes: Recent advances, CIRP Annals - Manufacturing Technology 60 (2011) p.603-626.

[2] B. Mikó, J. Beňo, Effect of the Working Diameter to the Surface Quality in Free-form Surface Milling, Key Engineering Materials 581 (2014) p.372-377.

[3] T. Otko, W. Zębala, Identification and analysis of residual stresses in the axisymmetric workpiece existing before and after machining, Key Engineering Materials 686 (2015) p. 33-38.

[4] J. P. Davim, Machining: Fundamentals and Recent Advances, (2008), Springer, ISBN 978-1-84800-212-8.

[5] J. Kundrák, G. Varga, Possibility of reducing environmental load in hard machining. Key Engineering Materials 496 (2011) p.205-210.

[6] J. Kundrák, G. Szabó, A. P. Markopoulo, Numerical investigation of the influence of tool rake angle on residual stresses in precision hard turning, Key Engineering Materials (2016) DOI:10.4028/www.scientific.net/ KEM.686.68

[7] F. Valiorgue, J. Rech, H. Hamdi, P. Gilles, J. M. Bergheau, 3D modeling of residual stresses induced in finish turning of an AISI304L stainless steel, Intern. Journal of Machine Tools and Manufacture 53/1(2012), p.77–90.

[8] M.M.A. Khan, M.A.H. Mithu, N.R. Dhar, Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid, Journal of Materials Processing Technology 209 (2009), p. 5573-5583.

[9] M. Nalbant, H. Gökkaya, G. Sur, Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning, Materials and Design 28 (2007), p. 1379-1385.

[10] User’s Manual of AdvantEdge v7.2 machining simulation software, (2016) Minneapolis, MN.