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A STUDY ON PREDICTION OF RESIDUAL STRESS ON THE SURFACE LAYER OF WORKPIECE WHEN GRINDING AISI 1045 STEEL

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ABSTRACT

This article presents a study on prediction of residual stress on the surface layer of workpiece when grinding AISI 1045 steel. Johnson-Cook's material model has been applied to build a relationship between residual stress on the surface layer and the parameters of the machining process. That relationship is used to predict the value of residual stress when grinding. The results of prediction of residual stress were compared with the experimental results. The results show that the residual stress value when predicting is quite close to the value when experimenting. The average deviation between the predicted results and the experimental results is only about 14.18%. The results of this study offer a promising method for predicting residual stresses on surface layer when grinding AISI1045 steel.

KEYWORDS: Johnson-Cook's Material Model, Prediction of Residual Stress when Grinding & AISI 1045 Steel

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Original Article

1. INTRODUCTION

Grinding is a popular processing method used in mechanical engineering. When researching on the grinding process, parameters are often chosen as criteria to evaluate the efficiency of the machining process such as surface roughness, cutting force, residual stres on surface layer. The residual stress on the surface layer of machine part has a great influence on the ability of the part to work through the effect of the residual stress on the fatigue strength of the product.The study of residual stress on surface layer of parts when grinding has been carried out by a number of scientists. Haifa Sallem et al. [1] studied the determination of residual stress on the surface layer when grinding high-speed steel (HSS) outside with CBN grinding wheel. Brosse et al. used SYSWELD software to determine the residual stresses on surface layer using finite element analysis. Zhenguo Nie et al. [2] conducted a simulation of prediction of residual stress on surface layer using a coupled thermo-mechanical modeling method based on FEM analysis of the cutting process of a abrasive grain, then they conducted experiments to evaluate the simulation results when grinding 2Cr12Ni4Mo3VNbN steel with WA400x30x27A80L5V35 grinding wheel. Chen et al. [3] simulated the residual stress on surface layer when grinding by assuming heat source infuses the surface of parts processed in triangular and rectangular form, and then they conducted the experiments of grinding En9 steel with 19A60L7V grinding wheel to verify the simulation results. Mahdi et al. [4] analyzed the effect of grinding heat on residual stress on surface layer when grinding based on analysis of phase transformation of materials, then they conducted the experiment of grinding EN23 steel to evaluate the accuracy of the calculated results compared with the experimental results. Leonardo Roberto da Silva et al. [5] conducted experiments to determine residual stress on surface layer when grinding AISI 4340 steel with FE38A60KV grinding wheel. Hockin et al. [6] investigated residual stress on surface layer when using diamond grinding wheel with four different grain sizes of 80, 150, 320 and 600 to grind two materials: polycrystal zirconia (Y-TZP) and a zirconia-toughened alumina (ZTA). Zhang et al. [7] conducted experiments to determine the influence of the cutting speed, the feed-rate and the cutting depth to residual stress on surface layer when using WA60L6V grinding wheel to grind 42CrMo steel. LeMaster et al. [8] experimented to determine the effect of the grinding depth on the change of stress on the gear surface when using vitrified alumina grinding wheel for grinding gears made of hard material 58 - 62HRC. Gunwant et al. [9] used ANSYS software to simulate the residual stress on surface layer when grinding AISI 52100 steel. Guoxian Xiao et al. [10] studied to build a model of residual stress on surface layer, and then conducted experiments when using CBN grinding wheel to grind camshaft of nodular cast iron material. Li et al. [11] experimented to investigate the effect of some machining conditions on residual stress on surface layer when using CBN grinding wheel to grind Ti-6Al-4V alloys (TC4 alloys). Xin-Chun HUANG et al. [12] investigated residual stress on surface layer when using SA80KV grinding wheel to grind GH4169 material. Stefan To¨nissen et al. [13] investigated residual stress when using B126N11VD47ST140 grinding wheel to grind 1.4108 (DIN-code) steel with hardness 62 HRC. HédiHamdi et al. [14] investigated the residual stress on surface layer when using two different types of grinding wheel, 2A60I6V and 2A80J7V, to grind AISI 52100 steel. Shouguo Shen et al. [15] investigated the residual stress on surface layer when grinding 3J33 Maraging steel with CBN grinding wheel. Grum et al. [16] used RAPOLD 8A60-H7B14 grinding wheel to investigate the residual stress when grinding 80WCrV8 steel, ect. In this study, we built a model to predict residual stress on surface layer when grinding ASIS 1045 steel. The predicted residual stress value was compared to the experiments.

2. BUILDING A MODEL TO DETERMINE RESIDUAL STRESS ON SURFACE LAYER WHEN GRINDING ASIS 1045 STEEL

ASIS 1045 steel is a medium carbon steel, high ductility, good welding. This steel is widely used in mechanical engineering, such as for the manufacture of axle, crankshaft, bolts, light and medium loaded gears. Equivalent symbols of ASIS 1045 steel of some countries are presented in Table 1. In Table 2 and Table 3 respectively, the chemical composition and some characteristics of ASIS 1045 steel.

Table 1: Equivalent of ASIS 1045 Steel [17]

USA	Germany	China	Japan	France	England	Sweden
ASTM/AISI/UNS/SAE	DIN, WNr	GB	JIS	AFNOR	BS	SS
1045/G10450	C22E/Ck22/1.1151	45	S45C	C45E/XC48	C40E/ 080M46	1660

Table 2: Chemical Composition ASIS 1045 Steel [18]

Element	C	Fe	Mn	P	S
[%]	0.42-0.50	98.51-98.98	0.6-0.9	≤0.04	≤0.05

Table 3: Characteristic Properties of ASIS 1045 steel [19]

Properties	Unit	Value
Tensile strength	MPa	585
Yield strength	MPa	450
Modulus of elasticity	GPa	200
Shear modulus	GPa	80
Posson's ratio	-	0.29
Elonggation at break (in 50 mm)	%	12
Hardness, Brinell	-	163
Hardness, Knoop (converted from Brinell hardness)	-	184
Hardness, Rockwell B	-	84
Hardness, Vickers (converted from Brinell hardness)	-	170
Thermal expansion coeficient	$\mu m/m^0C$	11.2

The Johnson-Cook stress model is shown as follows [20, 21, 22]:

$$\sigma = (A + B\varepsilon^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right) \quad (1)$$

Where σ is residual stress; A is initial yield strength; B is strain hardening coefficient; ε is equivalent plastic strain; $\dot{\varepsilon}$ is equivalent plastic strain rate; $\dot{\varepsilon}_0$ is reference plastic strain rate; n is Strain hardening exponent; C is strain rate coefficient; T is current temperature; T_r is reference temperature; T_m is melting temperature; m is thermal softening exponent.

For AISI 1045 steel, the value of some parameters in formula (1) is valid as shown in Table 4 [21, 22].

Table 4: Parameters of AISI 1045 Steel in Johnson-Cook Model

Parameter	A	B	n	C	$\dot{\varepsilon}_0$	T_m	m
Unit	MPa	MPa	-	-	s^{-1}	^0C	-
Value	553.1	600.8	0.243	0.0134	1.0	1400	1

About the values of equivalent plastic strain (ε) and equivalent plastic strain rate($\dot{\varepsilon}$) are quantities that are difficult to determine. When researching to determine the values of these quantities, scientists often use software such as ABAQUS, ANSYA, SYSWELD. Davim et al [23] used FEM analysis method to determine the value of these two parameters when processing AISI 1045 steel at normal speed (about 300 m/min) and when processing high speed (about 3000 m/min). The results of their research have determined that when processing at normal speed, equivalent plastic strain and equivalent plastic strain rate have corresponding values of 2.77 and 2.74x10^5(s^{-1}), while on high-speed machining, the values of equivalent plastic strain and equivalent plastic strain are respectively 2.36 and 6.3x10^6(s^{-1}).With the grinding method is the machining method where the cutting speed is very large. Thus, in this study, the value of equivalent plastic strain and equivalent plastic strain rate will be selected according to the research of Davim et al [23] in the case of high-speed machining. About the selected reference temperature $T_r = 27^0C$. Since then, the Johnson-Cook stress model of AISI 1045 steel is written as follows:

$$\sigma = (553.1 + 600.8 * 2.36^{0.243})\left(1 + 0.0134 * \ln\left(\frac{6.3*10^6}{1.0}\right)\right)\left(1 - \left(\frac{T-27}{1400-27}\right)^{0.662}\right) \quad (2)$$

Or:

$$\sigma = 1557.726 * \left(1 - \left(\frac{T-27}{1373}\right)^{0.662}\right) \quad (3)$$

Thus, in order to determine the residual stress, it is necessary to determine the value of the heat component acting on the part surface during machining T.

The relationship between cutting heat and grinding parameters is determined by the following equation[24]:

$$T = 1.13.\tau.\alpha^{1/2}.M^{n_1}\frac{1}{k}\frac{1}{12{,}5^{n_1}}\frac{1}{f^{\frac{n_1}{2}}}\frac{1}{r^{\frac{n_1}{2}}}t^{\frac{3-n_1}{4}}v_g^{n/4}v_w^{\frac{2-n_1}{4}}\left(\frac{d_g.d_w}{d_g+d_w}\right)^{\frac{1+n_1}{4}}\left(\frac{3s}{4\pi}\right)^{\frac{n_1}{2}} \quad (4)$$

Where τ is the ratio of heat transferred to the workpiece compared to the total heat source generated during the grinding process. When grinding Al_2O_3 wheel, the value of τ ranges from 60 to 90% [25]; when grinding CBN wheel, this value is about 84% [26]; α - is the thermal diffusivity of the part material, α can be found in [27]; M - is the mesh number used in the grading sieve of the grinding wheel;n_1 - is the positive coefficient, ranging from 0.8 to 1 [28];k - is the thermal conductivity of the material, k can be found in [29];f - is the ratio of the volume of the grinding grain cut to the surface of the part, f = 0.5 [30];r - is the chip width to thickness ratio, "r" ranges from 10-20 [31];t - is the depth of cut;v_g - is the speed of the grinding wheel;v_w - is the workpiece speed;d_g - is the diameter of the grinding wheel; d_w is the workpiece diameter, when surface grinding, $d_w = \infty$, so it can be considered $d_g . d_w/(d_g + d_w) = d_g$;s - is the percentage of the volume of the grinding grain compared to the total volume of the grinding wheel, s value ranges from 12.5% to 37.5% [32].

Combining equation (3) and equation (4) will be the relationship between residual stresses and parameters of the machining process when grinding AISI 1045 steel. This relationship allows to predict the value of residual stress in each grinding condition of AISI 1045 steel in each specific case.

3. COMPARISON OF RESIDUAL STRESSES WHEN PREDICTED AND WHEN TESTED

Experimental research data when examining the effect of cutting condition to residual stress on surface layer when grinding AISI 1045 steel with vitrified-bond aluminum oxide wheel (Norton 38A120-KVBE) of Yamin Shao [33] will be selected for comparison with the residual stress value when calculating in this study. Some parameters determined from the experimental conditions of Yamin Shao [33] are presented in Table 5.

Table 5: Parameters for Calculation Residual Stress

Parameters	Symbol	Value
Type of grinding wheel.	Norton 38A120-KVBE	
The diameter of the grinding wheel.	d_g	150 (mm)
The equivalent diameter of grinding wheel (surface grinding).	$\frac{d_g * d_w}{d_g + d_w}$	150 (mm)
The mesh number used in the grading sieve of the grinding wheel.	M	120
The thermal diffusivity of the part material.	α	5.8
The thermal conductivity of the material.	k	16.7 (W/mK)
The ratio of the volume of the grinding grain cut to the surface of the part.	f	0.5
The chip width to thickness ratio.	r	10
The positive coefficient.	n_1	1
The percentage of the volume of the grinding grain compared to the total volume of the grinding wheel.	s	0.2
The ratio of heat transferred to the workpiece compared to the total heat source generated during the grinding process.	τ	0.75
The speed of the grinding wheel.	v_g	23.94 (m/s)
The depth of cut.	t	15.24 (µm)
The speed of the workpiece.	v_w	1.524 (m/min) and 0.762 (m/min)

Use the data in Table 4 and Table 5 to calculate the value of residual stress according to two equations (3) and (4) in two different cases of the value of the workpiece velocity. Calculation results and experimental results are presented in Table 6. From the results in Table 6, the residual stress values are quite consistent compared to the experiments, with an average deviation of only about 14.17%.

Table 6: Value of Residual stress when Calculating and Experiment

No.	Parameter		Current temperature by Eq. (4), T (^{0}C)	Residual stress, δ (MPa)		Deviation of Residual stress (%)
	v_w (m/min)	Speed ratio (v_g/v_w)		Calculated	Measured [33]	
1	1.524	942.5	750.82	538.13	624	16.17
2	0.762	1885.0	631.36	652.89	582	12.18

4. CONCLUSIONS

This study applied Johnson-Cook's material model to build the relationship between the residual stress on surface layer and parameters of machining process when grinding AISI 1045 steel. The prediction has been compared with the experiment. The results show that the residual stress value when predicting is quite consistent with the value when experimenting. This shows that the results of this study can be used to predict residual stress on surface layeres when grinding AISI 1045 steel in each specific case of grinding method, type of grinding wheel, parameters of technology. This significantly reduces machine adjustment cost, test machining cost, contributes to improving the economic and technical efficiency of the AISI 1045 steel grinding process.

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