International Journal of Science, Environment and Technology, Vol. 3, No 4, 2014, 1347 – 1358

ISSN 2278-3687 (O)

STRESS DISTRIBUTION IN GRINDING BY FINITE ELEMENT ANALYSIS

Bijoy Das[1], Arup Kumar Biswas[2] and Santanu Das[3]

[1]Development Consultants Pvt. Ltd, Block DG-4, Sector II, Salt Lake City, Kolkata-700 091, West Bengal, India

[2]Assistant Professor, Department of Mechanical Engineering, Kalyani Government Engineering College, Kalyani- 741235, West Bengal, India

[3]Professor, Department of Mechanical Engineering, Kalyani Government Engineering College, Kalyani- 741235, West Bengal, India

E-mails: [1]bijoy.kgec@gmail.com, [2]arupkumar_biswas@yahoo.com, [3]sdas.me@gmail.com

Abstract: Grinding process is generally used for making products requiring high surface finish. However, due to high thermo-mechanical load, stresses are generated inside the ground workpiece. Residual stress, if tensile in nature, has detrimental effect on the workpiece. Thus, assessment of residual stress is important for fatigue analysis, safety design and strength evaluation. In this paper, a finite element thermo-mechanical model is used for evaluating distribution of stress induced during surface grinding of titanium Grade-1 flats. The stress generated in the product can be minimized by using coolant. Wet with pneumatic barrier condition gives more control on stress generation due to effective cooling. Stress generated during grinding can be controlled by controlling infeed also. Through analytical approach, it is found that simulation of experimental findings becomes possible. Therefore, using this technique, requirement of rigorous experimentation may be reduced significantly.

Keywords: Grinding; Surface grinding; Stress distribution; Thermo-mechanical stress; Finite element analysis.

1 INTRODUCTION

Grinding is a widely used finishing or semi-finishing machining process. This is characterized by high wheel material removal rate, high specific force and energy requirement, and high heat generation. The high energy required for grinding per unit volume of material removal is mostly converted to heat energy. Some part of this energy goes into the workpiece from grinding zone resulting in many thermal related problems in grinding. This also affects the ground work-piece by increasing the tendency for formation of tensile residual stress that is harmful under the application of fatigue loading [1, 2]. Temperature can be controlled by changing process parameters, wheel characteristic, dressing technique, fluid

*Received June 21, 2014 * Published August 2, 2014 * www.ijset.net*

type, fluid delivery technique, fitting scrapper board before the fluid delivery, using rexine pasted wheel and cryogenic cooling [2-6].

The work of Palhade et al. [7] and Yang and Shaw [8] on grinding of titanium showed that it is difficult to grind the titanium for its high chemical reactivity, high strength, high hardenability, and low thermal conductivity causing high grinding temperature, wheel loading, wheel material removal, grit wear, etc. Karyuk [9] work on titanium grinding have shown that it has high strength to weight ratio , excellent corrosion resistance and ability to make good surface finish, but after grinding it losses 20-25% of strength from that before grinding. Turley [10] found the factors affecting surface finish while grinding of titanium and titanium alloy. Mandal et al. [11] explored grindability of titanium grade1 using a pneumatic barrier. In Pneumatic barrier set up compressed air pressure is applied through nozzle to restrict the stiff air layer around grinding wheel. Mandal et al. [12, 13] observed that maximum of 53 % reduction of air pressure is possible by using pneumatic barrier that helps to penetrate the grinding fluid to enter deep inside the grinding zone. This method save large amount of grinding fluid that leads to environmental pollution [13].

Many efforts were made to measure and control the residual stress by selecting appropriate process variables such as feed rate, wheel characteristics such as bond structure and type of abrasive grain, dressing techniques, type of grinding fluid or fluid delivery technique, etc [14].

Brosse et al. [15] determined temperature field under the ground surface by thermography. Value and shape of heat flux could be identified by this method. Malkin and Anderson [16] estimated the maximum temperature considering uniform heat flux. Xiao et al. [17] derived a Temperature distribution function and Mao et al. [18] also analysed the temperature field in wet surface grinding. Guo and Malkin [19] used the analytical methods to find the grinding temperature. Tahvilian et al. [20] predicted temperature field and the energy partition at the wheel–workpiece interface by three dimensional finite element modelling and experimental observations. On the other hand, Narayan and Yadava [21] developed a two dimensional thermal-based finite element model to investigate the transient temperature distribution within the contact zone as well as in the whole workpiece due to creep feed grinding [21]. Doman et al. [22] reviewed the two and three dimensional modeling approaches and categorized them in macroscopic and microscopic approaches. Shah et al. [23] performed mechanical and thermo-metallurgical analysis to model the mechanical, thermal and, metallurgical behaviour of a ground workpiece. Rossini et al. [24] reviewed different residual stress measurement technique and also summarized the scope, limitation, advantage and disadvantage of advanced techniques. Desruisseaux [25] assumed total thermal power generated by the grinding process to be equal to the net grinding power. This consideration is widely used by many researchers [19, 26-28] and found satisfactory results. Brosse et al. [29] predicted residual stresses in grinding with a new thermo mechanical simulation.

In this work, a thermomechanical finite element modeling of a surface grinding process is done. Influence of grinding infeed and environment on the distribution of residual stresses in the workpiece is explored. Three different environmental conditions are considered in this study, such as dry, wet and wet with pneumatic barrier conditions. From the heat flux distribution, temperature distribution in the workpiece is obtained. Finally, analysis is done to compute the stress distribution in the workpiece due to thermal loading as well as structural loading. Final values are obtained by summing up the stress due to thermal and structural loading at different infeeds and environment. The influence of grinding environment and infeed on the distribution of residual stresses in the workpiece is also studied.

2 DETAILS OF THE ANALYTICAL WORK DONE

2.1 Temperature distribution in the grinding zone

Heat generation in the contact area of grinding wheel and workpiece is mainly due to rubbing action and plastic deformation. This grinding zone temperature and its subsequent cooling are the main reason for generation of residual stress. As the workpiece enters grinding zone, it will be progressively heated till the grinding wheel leaves the workpiece. Under the influence of grinding fluid, the workpiece gets cooled to room temperature at a high rate.

Maximum temperature, T_{max} on the workpiece can be estimated by using the empirical equation by Malkin and Anderson [16]. By putting the value of heat flux as 1035.61 W/m^2. T_{max} was found to be 470°C in this work. Here rectangular (uniform) heat flux distributions are used for calculating grinding temperature. However, the purpose of this work is to find out the temperature distribution in the workpiece and not the maximum temperature.

In the present work, temperature distribution is evaluated using Finite element analysis, and is compared with the result obtained by the equation proposed by Xiao et al. [17].

Fig 1: The pneumatic barrier arrangement

2.2 Net grinding power

This model rests on the assumption proposed by Desruisseaux [25] that is widely used by many researchers [19, 26-28]. They used the expression of total thermal power, P_{th} given by

$$P_{th} = P_m = F_t (V_s \pm V_w) \quad (1)$$

Where F_t is the tangential grinding force (N),

V_s is the peripheral wheel velocity (m/s).

V_w is the velocity of workpiece (m/s)

As V_w is negligible compared to V_s, therefore, the above equation becomes

$$P_{th} = F_t .V \quad (2)$$

Belgian Research Center for Manufacturing Industry (CRIF) [28] proposed an expression of grinding force according to the equivalent chip thickness h_{eq} (μm) given by

$$F_t = F^1{}_t .(h_{eq})^n \text{ for } 0.03 \le h_{eq} \le 0.3\mu m, \quad (3)$$

Where $F^1{}_t$ is the tangential grinding force for an equivalent chip thickness equal to one, and n is an empirical exponent. The equation (3) can be simplified as follows:

$$F_t (b, ap, V_w, V_s) = 20b.a_p (V_w/V_s)^{0.615} \quad (4)$$

So for wheel velocity, V_s of 30 m/sec, table feed (work velocity), V_w of 7.5 m/min and wheel width 13 mm, as used in the present work, tangential grinding force for different infeed and can be estimated. Fig. 1 shows the wheel with the probes fitted. With equation (2) and (4), the net grinding power for different infeed is calculated in the present work and given in Table 1.

Table 1 Net grinding power generated under different conditions

Infeed (Micron)	Environment	Net Grinding Power (W)
10	Dry	1184
	Wet	1002.4
	Wet with pneumatic barrier	1002
20	Dry	1656.2
	Wet	1472.2
	Wet with pneumatic barrier	1380.2
30	Dry	2292.3
	Wet	1932.2
	Wet with pneumatic barrier	1564.2

2.3 Heat flux entering the workpiece

To evaluate the fraction of net heat flux density entering the workpiece (φ_w), the need is to quantify accurately the parts of the net heat flux going through grinding wheel (φ_s), chip and the grinding fluid (φ_c). This evaluation must recognize different parameters such as thermal properties of the wheel, temperature of chip or heat exchange with the grinding fluid. The fraction of heat entering the workpiece is calculated using the results of Guo and co-workers [19]. In fact, Kohli et al. [27], Rowe et al. [28] and Chen et al. [26] worked for a long time on the thermal aspects of the grinding process using embedded thermocouples. They found that 60–75% of the net grinding energy enters the workpiece as heat using an alumina grinding wheel. So, net power entering the workpiece, P_w can be written as:

$$P_w = \int \varphi_w ds = \varepsilon P_m$$

Where, ε is given by $\varepsilon = 1 - 0.45 \frac{U_{ch}}{U}$

Kohli et al. [27] found the value of ε to be 0.65. Assuming this value of ε as 0.65 the different value of grinding energy entering the workpiece is calculated and tabulated in Table 2.

Table 2 Grinding energy entering the workpiece for different condition

Infeed (Micron)	Environment	Grinding energy entering the workpiece (W)
10	Dry	796.6
	Wet	651.6
	Wet with pneumatic barrier	651.3
20	Dry	1076.5
	Wet	956.9
	Wet with pneumatic barrier	897.1
30	Dry	1555
	Wet	1932.2
	Wet with pneumatic barrier	1016.7

2.4 Heat flux distribution on the contact area

For the modeling of the simplified heat source it is essential to know the heat flux density, φ_w which is passed from the heat source to the workpiece. Due to different values of tangential force at different grinding conditions, values of heat flux entering the workpiece are different. Brosse et al. [29] calculated heat flux density, φ_w as

$$\varphi_w = \frac{2P_w}{bl_c^2} X$$

Where X is the curvilinear abscissa associated with the contact area, b and l_c are wheel width and arc length of the wheel respectively.

Putting the value of P_w, b, l_c and X different values of heat flux density entering the workpiece are calculated as shown in Table 3.

Table 3 Value of Heat flux density under different grinding conditions

Infeed (Micron)	Environment	Heat flux entering the workpiece (W/m^2-K)
10	Dry	512.6
	Wet	433.9
	Wet with pneumatic barrier	433.7
20	Dry	717
	Wet	637.3
	Wet with pneumatic barrier	597.5
30	Dry	1035.6
	Wet	836.5
	Wet with pneumatic barrier	677.1

2.5 Various inputs for analysis

The present analysis is done to compute temperature and stress at every node by Finite Element software, ANSYS. The software also gives temperature distribution and stress distribution in the workpiece in two situations, when the temperature of the workpiece increases due to grinding wheel and workpiece interaction, and then during the time when temperature of the workpiece decreases due to cooling.

In this work, the workpiece material is titanium Grade 1 that has material composition of C- 0.1%, Fe- 0.2%, H- 0.015%, N- 0.03%, O- 0.18% and Ti-99.55% by weight [11, 30]. For this work, thermal properties of Ti-Gr. 1 are considered detailed in Table 4. Boundary conditions considered are:

Displacement of the bottom surface of the workpiece is zero in each direction. Also the displacement of the portion which is in contact with the grinding wheel is also considered zero.

All surfaces of the workpiece are supposed to exchange heat with the grinding fluid. A heat exchange coefficient h = 4 ×10-4 W/m2-K2 and a fluid temperature equal to 20°C are then considered. The initial temperature of the workpiece is taken 20°C. The value of net grinding energy entering the workpiece is calculated for different values of feed and environment. By considering wheel infeed a_p of 10µm, 20µm and 30µm, different values of heat flux density are obtained. The workpiece has a uniform moving speed, Vw of 7.5 m/min. So the speed of the moving heat flux is considered to be 7.5 m/min. The vitrified bonded alumina grinding wheel width, b = 13 mm. In this work, a movable uniform thermal heat flux has been considered for transient thermal analysis. In this paper the stress distributions are computed in two steps. First, the temperature and stresses distribution are calculated using a steady-state assumption. Then, from the results of the steady-state calculation, the final cooling is simulated in order to get the final residual stresses. For each steps, the thermomechanical calculation is performed in two steps. First, a thermal analysis is performed considering the temperature distribution in the workpiece. Then, a structural analysis using the temperatures previously computed to compute the stress distributions.

Table 4 Thermal properties of materials

Thermal properties	Unit	Values
Thermal Conductivity, k	W/m-K	16
Specific Heat, C	J/kg-∘C	520
Density of Material, ρ	kg/m3	4510
Modulus of Elasticity, E	GPa	105
Thermal expansion co-efficient, α	mm/mm°C	3.6x10-5

The grinding wheel rotational speed is 2900 rpm and it has a diameter of 200 mm. So the length of heat Flux which is equal to geometrical contact length of the wheel workpiece interface is = $\sqrt{a_p d_s}$, where a_p is Infeed and d_s denote wheel diameter. The length of heat flux is different for varying infeed and is given in Table 5.

Table 5 Length of heat flux for different grinding conditions

Infeed (μm)	10	20	30
Length of heat flux (mm)	1.414	2	2.449

3 RESULTS AND DISCUSSION

3.1 Temperature profile in different conditions

Due to different values of heat flux, temperature profile would be different for different grinding conditions. In this work, temperature variation for varying distance from the grinding zone at an instant is analyzed, and is found to be linear in nature as material properties considered are linear. If nonlinear material property is considered, the temperature variation with distance from grinding zone would be non linear as reported in references [18]. For 30 micron infeed, temperature distribution pattern is similar to that with 20 micron infeed. Only difference is that at 30 micron infeed the maximum temperature generation is higher than that of the infeed of 10 and 20 micron corresponding to higher forces acting on the workpiece. So heat flux entering the workpiece is higher and consequently, maximum temperature generated is higher.

The stress distributions for 20 micron infeed under different environmental conditions are shown in figure 2-4. The pattern for stress distribution is similar as seen in Fig 2-4. However values of stress at different nodes are formed to be varying

Stress distribution during grinding at the infeed of 10 μm and 30 μm shows similar pattern of stress distribution observed with an infeed of 20 μm. Main difference is the value of stress.

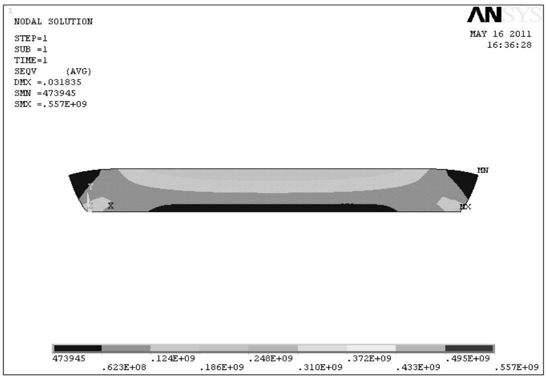

Fig.2 Stress distribution with the infeed of 20 micron in dry condition

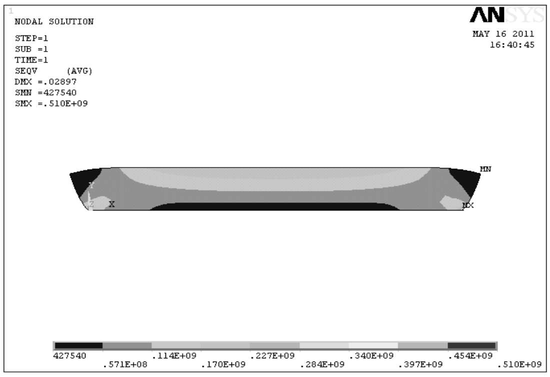

Fig. 3 Stress distribution with the infeed of 20 micron in wet condition

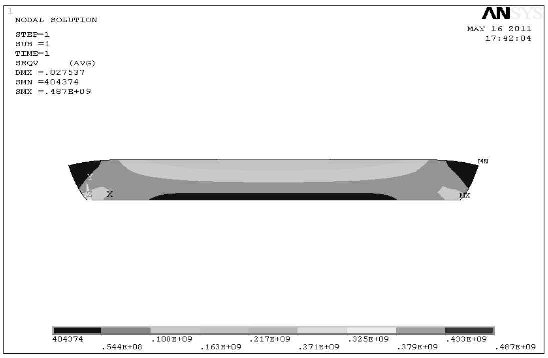

Fig. 4 Stress distribution with the infeed of 20 micron wet with pneumatic barrier condition

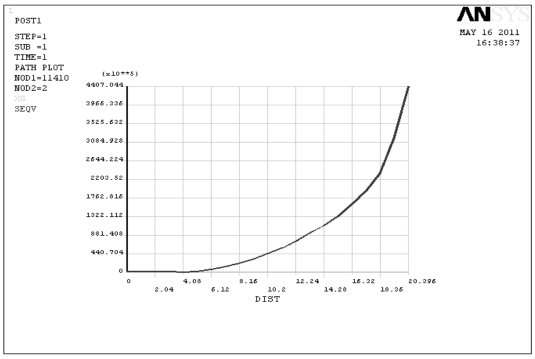

Fig. 5 Stress variation with increasing depth with the infeed of 20 μm in dry condition

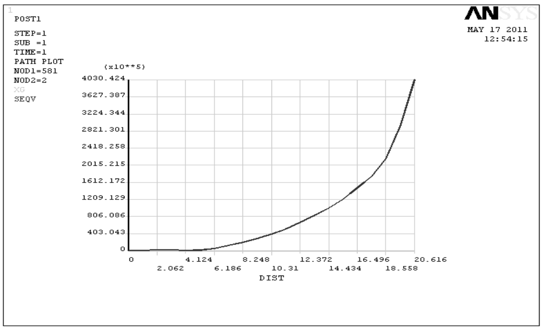

Fig. 6 Stress variation with the increasing depth with the infeed of 20 µm in wet condition

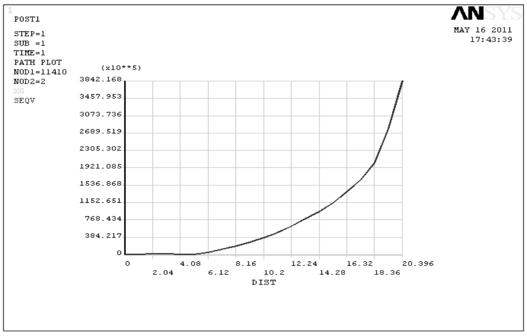

Fig.7 Stress variation with the increasing depth with the infeed of 20 µm in wet with pneumatic barrier wet condition

Maximum stress generation is found to be different for different values infeed and grinding environment. Table 6 depicts the maximum value of stress for different infeed and grinding environment.

Table 6 Maximum stress noted under different conditions

Infeed (Micron)	Environment	Maximum Stress (MPa)
10	Dry	437
	Wet	391
	Wet with pneumatic barrier	390
20	Dry	557
	Wet	510
	Wet with pneumatic barrier	487
30	Dry	745
	Wet	627
	Wet with pneumatic barrier	534

The stress generated in the product can be minimized by using coolant. Good cooling facility gives reduced stress. In this analysis, higher stress is generated in grinding at 30 µm in dry condition and this value is 745 MPa. Stress value decreases after the use of coolant. Maximum stress in wet condition with pneumatic barrier is less than that in wet condition. At higher infeed, higher will be the grinding force component, and naturally high temperature generated at the wheel workpiece interface causes metallurgical transformation, and when it is cooled down to room temperature, compressive stress is generated due to contraction and metallurgical transformation, whereas thermal effect at lower wheel velocity causes tensile Stresses.

3.2 Variation of stress with distance from grinding zone

Variation of stress with distance from grinding zone at 20 µm infeed under dry, wet and wet with pneumatic barrier condition is depicted in Fig 5-7 respectively. The pattern of variation of stress with distance from grinding zone for 10 and 30 µm infeed is also quite similar to that observed with 20 µm infeed under varying environmental conditions

It is observed that the stress distributions for Wet condition and wet with pneumatic barrier, at low infeed have small differences as the temperature distribution and force distribution are having fewer differences. Main contribution on total stress of a ground workpiece is from its tensile part. Small part is contributed by compressive stress. Total stress value increases with the increase of infeed when other conditions remain same. Also principal stress comes from two loading, one is due to mechanical force and another is from thermal loading so transient analysis for structural analysis and thermal analysis is performed simultaneously.

4. CONCLUSION

In the present work, stress distribution in grinding is computed by a general purpose Finite Element code (ANSYS software) under different infeeds and environmental conditions.

From the work done, following conclusions may be drawn:

1) Stress varies proportionally with the infeed ie at high infeed higher tensile Stress is generated so total stress is higher at high infeed whereas at lower infeed total stress generated is less.

2) The tensile stresses generated in grinding are higher compared to the generated compressive stresses.

3) Induced stress is dependent not only on the maximum temperature rise at the surface but also on the temperature gradient at the surface.

REFERENCES

[1] Malkin, S., Grinding Technology: Theory and Application of Machining with Abrasives, Ellis Harwood Publication, UK, 1990.

[2] Bhattacharyya, A. Metal Cutting Theory and Practice; Central Book Publishers, Kolkata, 1984.

[3] Das, S., Improving grinding performance through appropriate grinding fluid application, Proceedings of the National Conference on Investment Casting, Durgapur, India, 2003, 97-103.

[4] Das, S.; Sharma, A.O.; Singh, S.S.; Nahate, S.V. Grinding performance through effective application of grinding fluid, Proceedings of the International Conference on Manufacturing, Dhaka, Bangladesh, 2000, 231-239.

[5] Putatunda, S., Bandyopadhyay, A.K., Bose, T., Sarkar S. and Das, S., On the Effectiveness of applying grinding fluid in surface grinding, Proceedings of the National Seminar on Emerging Trends in Manufacturing, XVI National Convention of Production Engineers, Varanasi, India, pp.182-187, 2002.

[6] Chattopadhyay, A. B., Lecture note delivered at Tata Bearing, 24.10.1992.

[7] Palhade, R.D.; Tungikar, V.B.; Dhole, G.M.; Application of Different Environments in Grinding of Titanium Alloys (Ti-6Al-4V): Investigations on Precision Brazed Type Monolayered Cubic Boron Nitride (CBN), Grinding Wheel, Institution of Engineers (India), Production Engineering Division, 2009, 90, 9-13.

[8] Yang, C.T.; Shaw, M.C. The Grinding of Titanium Alloy. Transactions of the ASME, 1955, 77, 645-660.

[9] Karyuk, G.G. Effect of Grinding on the Structure of the Ti-alloys. Institute of Material Science, Ukrain, SSR, 1978, 192, 12, 69-75.

[10] Turley, D.M., Factors Affecting Surface Finish when Grinding Titanium and Titanium Alloy (Ti-6Al-4V) Materials. Research Laboratories, Defence Science and Technology Organization, Australia, 1985, 104, 4, 223-235.

[11] Mandal, B.; Biswas, D.; Sarkar, A.; Das, S.; Banerjee, S. Exploring Grindability of titanium grade1 using a pneumatic barrier. Reason- A Technical Journal 2013, 12, 37-45.

[12] Mandal, B.; Singh, R.; Das, S.; Banerjee, S. Development of a Grinding fluid delivery technique and its performance evaluation. Materials and Manufacturing Processes 2012, 27(4), 436-442.

[13] Mandal, B.; Das, G.; Das, S.; Banerjee, S. Improving grinding fluid delivery using pneumatic barrier and compound nozzle. Prod. Eng. Res. Devel. 2014, 8(1-2), 187-193.

[14] Singh, V.; Rao, P.V.; Ghosh, S. Development of specific grinding energy model. International Journal of Machine Tools and Manufacturing 2012, 60, 1-13.

[15] Brosse, A.; Naisson, P.; Hamdi, H.; Bergheau, J.M. Temperature distribution and heat flux characterization in grinding using thermography. Journal of Material Processing Technology 2008, 201, 590-595.

[16] Malkin, S.; Anderson, R.B. Thermal aspects of grinding, Part2: Surface temperatures and workpiece burn. Transaction of the ASME, Journal of Engineering for Industry 1974, 11, 1184–1191.

[17] Xiao, G.; Stevenson, R.; Hanna, I.M.; Hucker, A.S. Modeling of residual stress in grinding of nodular cast iron. Journal of Manufacturing Science and Engineering 2002, 124, 833.

[18] Mao, C.; Zhou, Z.X.; Ren, Y.H.; Zhang, B. Analysis and FEM simulation of temperature field in wet surface grinding. Materials and Manufacturing Processes 2010, 25, 399-406.

[19] Guo, C.; Malkin, S. Analysis of transient temperatures in grinding. Journal of Engineering for Industry 1996, 117, 571-577.

[20] Tahvilian, A.M.; Liu, Z.; Champliaud, H.; Hazel, B. Experimental and finite element analysis of temperature and energy partition to the workpiece while grinding with a flexible robot. Journal of Materials Processing Technology 2013, 213(12), 2292-2303.

[21] Narayana, A.; Yadavaa, V. Investigation of temperature distribution in the workpiece during Creep feed surface grinding using finite element method. Materials and Manufacturing Processes 2012, 27(10) 1101-1109.

[22] Doman, D.A.; Warkentin, A.; Bauer, R. Finite element modeling approaches in grinding. International Journal of Machine tools & Manufacture 2009, 49, 109–116.

[23] Shah, S.M.; Nelias, D.; Zain-ul-abdein, M.; Coret, M. Numerical simulation of grinding induced phase transformation and residual stresses in AISI-52100 steel. Finite Elements in Analysis and Design 2012, 61, 1-11.

[24] Rossini, N. S.; Dassisti, M.; Benyounis, K.Y.; Olabi, A.G. Methods of measuring residual stresses in components. Material & Design 2012, 35, 572-588.

[25] Desruisseaux, N. Thermal aspect of grinding process. Ph.D. thesis, University of Cincinnati, Cincinnati, US, 1968.

[26] Chen, X.; Rowe, W.B.; McCormack, D.F. Analysis of the transitional temperature for tensile residual stress in grinding. Journal of Material Processing Technology 2000, 107, 216–221.

[27] Kohli, S.; Guo, C.; Malkin, S. Energy partition to the workpiece for grinding with aluminum oxide and CBN abrasive wheel. Transaction of the ASME. Journal of Engineering Industry 1995, 117, 160–168.

[28] Rowe, W.B.; Pettit, J.A.; Boyle, A.; Moruzzi, J.L. Avoidance of thermal damage in grinding and prediction the damage threshold. Annals of the CIRP 1988, 37(1), 327- 330.

[29] Brosse, A.; Hamdi, H.; Bergheau, J.M. Residual Stresses prediction with a new thermo mechanical simulation of grinding. International Journal of Material Forming 2008, 1(1) 1319-1322.