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HEAT DISTRIBUTION WHEN NICKEL ALLOY GRINDING

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Preliminary notes
Heat distribution in machining is one of the phenomenological characteristics of this process because it significantly influences functional properties of machined surfaces. This paper deals with heat distribution during grinding of Ni alloy and its relationship to the quality of ground parts in terms of residual stresses. The analysis of the heat distribution is based on measurement of the temperature in the contact of the grinding wheel and the workpiece, and the tangential component of cutting force. The heat distribution when Ni alloy grinding differs from the heat distribution when grinding a conventional Fe alloy such as roll bearing steel mainly because of the low heat conductivity of Ni alloys. Also, the application of CBN and diamond grinding wheels significantly reduce the thermal exposition of the ground parts, primarily when applying cutting fluid. This fact significantly influences the residual stresses after grinding. The results of the analysis show that there is correlation between energy partitioning and residual stresses.

Keywords: *grinding, Ni alloy, heat distribution, temperature, residual stresses*

Razdioba topline kod brušenja nikaljnih legura

Prethodno priopćenje
Stvaranje i razdioba topline tijekom obrade odvajanjem čestica jedna je od fenomenoloških karakteristika tih postupaka, koja znatno utječe na funkcionalnost obrađenih površina. Rad se bavi proučavanjem distribucije topline tijekom brušenja nikaljnih legura i njenim utjecajem na kvalitetu brušenih površina uslijed pojave napetosti (zaostalih naprezanja). Analiza razdiobe topline temelji se na mjerenju kontaktnih temperatura između brusnog kotača i obradka te tangencijalne komponente sile rezanja. Razdioba topline tijekom brušenja nikaljnih legura različita je od one tijekom brušenja uobičajenih željeznih legura, primjerice čelika za kotrljajuće ležajeve, prvenstveno zbog njihove niže toplinske provodnosti. Također, uporaba bor-nitridnih (CBN) i dijamantnih bruseva značajno smanjuje toplinska opterećenja obradaka, prvenstveno uz uporabu rashladnih fluida. Ta činjenica znatno utječe na pojavu napetosti nakon brušenja. Rezultati analize pokazuju da postoji povezanost između razdiobe toplinske energije i napetosti.

Ključne riječi: *brušenje, nikaljne legure, razdioba topline, temperatura, napetosti*

1 Introduction

Nickel and its alloys are attractive materials due to their high strength that is maintained at elevated temperatures and their exceptional corrosion resistance. Ni alloys are classified as difficult-to-machine materials. Machined parts made of Ni alloys are usually exposed to fatigue load because the major application of nickel has been in the aerospace and chemical industry. Gentle machining operations usually result in a high cyclic fatigue strength that is much higher than that of the corresponding abusive cutting conditions. The surface of Ni alloys is easily damaged during machining operations, especially during grinding. The main reason can be found in the strong adhesion of Ni alloy and so the grinding wheel has to be redressed in the short dressing intervals.

The grinding damage is usually thermally induced [1] and comes not just from the heat generated in the cutting zone, but also from the temperature on the surface of a ground part, its gradient and R_w coefficient – partition ratio (the ratio of the heat entering the workpiece to the total heat [2]). Residual tensile stresses, which are primarily thermal in origin, may be unacceptable.

Investigation has found that the preferred compressive stresses are more likely to be achieved with CBN and diamond grinding wheels. Results of investigations [3] indicate an advantage of CBN and diamond grinding is a smaller proportion of the energy entering the workpiece. The partition ratio is therefore a useful indicator of grinding wheel performance relevant to the likelihood of tensile stresses.

Most of energy enters the workpiece (90 %) when grinding conventional Fe alloys (such as roll bearing steels) and application Al_2O_3 grinding wheel [3, 4]. This is primarily caused by kinematics conditions. The secondary aspect is resulting from the different thermal conductivity between the conventional Fe alloys (for roll bearing steels 46 W/(m·K)) and Al_2O_3 grinding wheel (6 W/(m·K)). The heat distribution when grinding Ni alloys differs from the heat distribution when grinding conventional Fe alloys because of the poor thermal properties of Ni alloys (thermal conductivity of Ni alloys is 12,5 W/(m·K)). The heat generated in the cutting zone is concentrated on the ground surface and forms very high thermal gradient. It is well known that this gradient (except mechanical load and structure transformation) is decisive considering formation of stress state after cutting operations. This paper deals with analysis of heat distribution and its relation to the quality of ground parts represented by residual stresses.

2 Experimental method

Experimental analysis of heat distribution is based on "Moving Heat Source Theory" (Jaeger [5]). The heat source of constant heat flux per unit area q, length $2l$, moves along the surface of a semi-infinite stationary body at a constant velocity v_w. The origin of co-ordinate axes x, z is at the centre of the heat source. A two-dimensional, steady-state temperature distribution for this model is obtained as

$$\theta \cdot \frac{\pi \cdot k \cdot v_w}{2 \cdot q \cdot a} = \int_{X-L}^{X+L} e^{-u} \cdot K_0\left[\left(Z^2 + u^2\right)^{0,5}\right] du\,, \qquad (1)$$

where:

θ – temperature rise above ambient, °C
α – thermal diffusivity, m^2/s
k – thermal conductivity, W/(m^2·K)
q – heat flux, W/m^2
l – half length of band source, m
K_0 – the modified Bessel function, –
u – specific grinding energy, J/kg
X, Z, L – dimensionless quantities, –
$\left(X = \frac{v_w \cdot x}{2\alpha}, Z = \frac{v_w \cdot z}{2\alpha}, L = \frac{v_w \cdot l}{2\alpha}\right)$.

Takazawa obtained a solution for the equation (1) by numerical integration. Its simplified form is

$$\theta \cdot \frac{\pi \cdot k \cdot v_w}{2 \cdot R_w \cdot q \cdot a} = 3{,}1 \cdot L^{0{,}53} \exp(-0{,}69 \cdot L^{-0{,}37} \cdot Z), \qquad (2)$$

and the equation for a maximum temperature rise θ_d (z = 0) is

$$\theta_d = 0{,}947 \cdot \alpha^{0{,}47} \cdot k^{-1} \cdot F_c \cdot R_w \cdot v_c \cdot v_w^{-0{,}47} \cdot l_c^{-0{,}47}, \qquad (3)$$

where:
F_c – tangential force component, N
v_c – wheel speed, m/s
l_c – contact length, m.

$F_c \cdot v_c$ is the total energy created in the cutting zone Q. The energy partition R_w can be calculated by substituting the maximum temperature rise θ_d and the tangential grinding force F_c into equation (3).

The measurement of F_c was made with a piezoelectric KISTLER dynamometer together with the measurement of temperature. The temperature was measured by the thermocouple technique (Fig. 1) introduced by Peklenik [6] and improved by Gu and Wager [7] (both quantities measured through an A/D card to a PC).

Cutting conditions: v_c = 25 m/s, v_w = 4 m/min, grinding wheel A99 60LVS, surface plunge grinding, without and with cutting fluid (Emulzín H – 2 % concentration).

Machined materials:

- Ni alloy EI 698VD – thermal diffusivity α = 3,62 m^2/s, R_m = 1100 MPa at 500 °C, R_m = 1050 MPa at 700 °C, R_m = 700 MPa at 800 °C, $R_{p0,2}$ = 720 MPa at 500 °C, A = 26 % at 500 °C, Z = 35 % at 500 °C, 363 HB, workpieces 50 × 25 × 10 mm. Its chemical composition is given in Tab. 1.
- Fe alloy, roll bearing steel 14 209.4 (100CrMn6) (62 HRC) – thermal diffusivity 12,4×10^{-6} m^2/s. Its chemical composition is given in Tab. 2.

Table 1 Chemical composition of the Ni alloy EI 698 VD

Element	Ti	Cr	Si	Nb	P	S	Mo	C	Fe
%	2,3 ÷ 2,8	13 ÷ 16	≤ 0,5	1,9÷ 2,2	≤ 0,015	≤ 0,07	2,8 ÷ 3,2	≤ 0,03	≤ 2

Table 2 Chemical composition of the 14 209.4 hardened roll bearing steel

Element	Cr	Mn	Si	Cu	S	P	Ni	C
%	1,3 ÷ 1,6	0,9 ÷ 1,2	0,3-0,6	≤ 0, 25	≤ 0,03	≤ 0,03	≤ 0,3	1

3 Experimental results

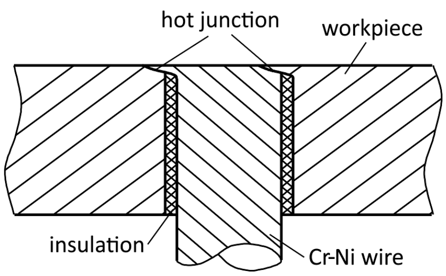

Figure 1 Peklenik method for measurement of temperature in the contact of grinding wheel and workpiece

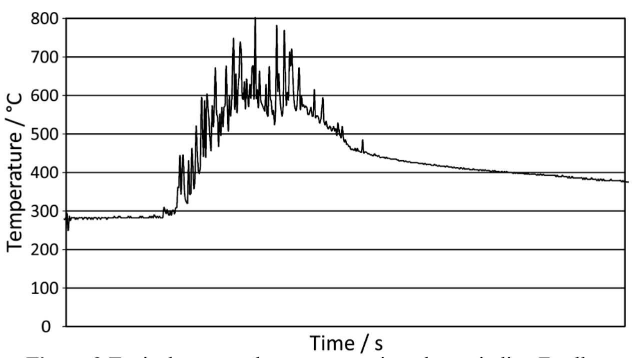

Figure 2 Typical measured temperature rise when grinding Fe alloy (a_p = 0,03 mm)

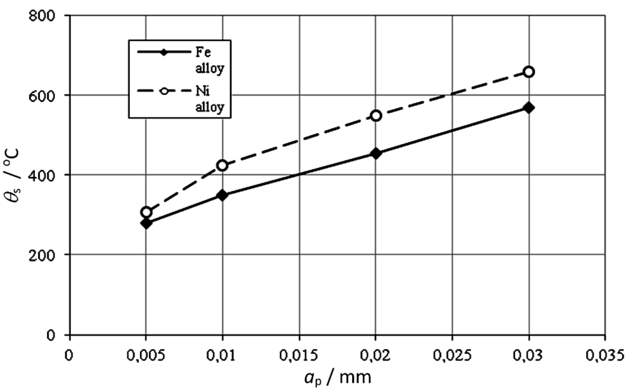

Figure 3 Influence of a_p on the surface temperature for Fe and Ni alloy

The temperature on the surface θ_s was obtained by putting a smooth curve through the measured trace (Fig. 2). Fig. 3 presents a relation between surface temperature and the cutting depth. The total heat was determined by measuring the tangential force and wheel speed (Fig. 4). The partitioning ratio R_w (Fig. 5) is the portion of the heat entering the workpiece to the total heat calculated by substituting the maximum temperature rise θ_s from Fig. 3 and the tangential grinding force F_c from Fig. 4 into Eq. (3).

In grinding operation almost all the grinding energy is converted into heat within a small grinding zone. There are three significant heat sinks in dry grinding: workpiece, grinding wheel and grinding chips. The maximum possible heat entering grinding chips may be expressed in terms of the specific metal removal, the density, the specific heat capacity and the difference between the melting temperature and the ambient temperature [8]. On the basis of this assumption the maximum heat entering the grinding chips is about 8 % for Fe alloy and 6 % for Ni alloy.

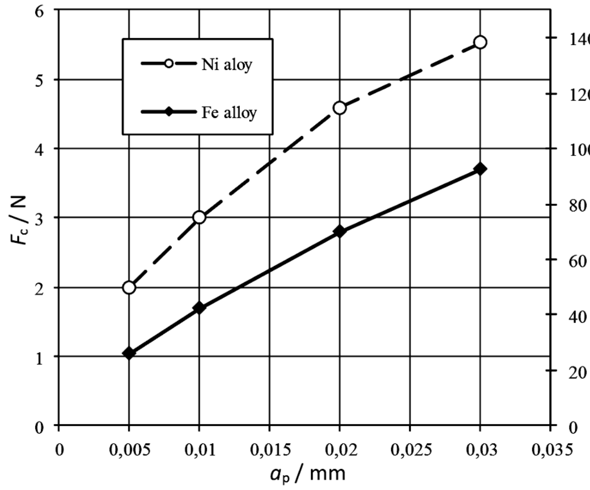

Figure 4 Total heat Q and tangential component of grinding force F_c per 1 mm of grinding width

A large part of the generated heat flows into the workpiece (Q_w), which results in extremely high temperatures at the interface between the wheel and the workpiece. On the basis of the experimental results it is possible to verify that a small portion of energy enters the grinding wheel (Q_k) when grinding hardened steel. On the other hand about 65 % of the heat is entering the grinding wheel when grinding nickel alloy (Fig. 8). The high mechanical and thermal load of grains when grinding the nickel alloy leads to a high grain wear rate, low G ratios (while G ratios for Fe alloy can reach 60 $mm^3 \cdot mm^{-3}$, the high mechanical and thermal load during grinding Ni alloy strongly reduce this ratio and G ratios from 1,5 to 8 $mm^3 \cdot mm^{-3}$ can be obtained) and the strong adhesion between the machined material and the cutting grain [9]. The maximum temperature rise for Ni alloy is higher than that for Fe alloy although the net energy input for the Ni alloy is lower than for the Fe alloy (Fig. 7). This is because the thermal conductivity of the Ni alloy is much smaller than that of the hardened steel (the concentration of heat in the contact of the grinding wheel and workpiece when grinding the Ni alloy).

The results of the next experiments show that the use of diamond and CBN grinding wheels reduces the tendency to induce thermal damage to the ground surfaces of parts made of the Ni alloy. The surface temperatures for the CBN and diamond grinding wheels (except dry grinding of Ni alloy), measured with the same technique are significantly lower than those measured for Al_2O_3, primarily when applying cutting fluid (Emulzín H 2 % concentration), Tab. 3. The values of the partitioning ratios are much lower with CBN and diamond grinding and the use of cutting fluid (Tab. 4 and Fig. 6). Ni alloy adheres on the grinding grains and creates a strong barrier for heat transfer (mainly when using CBN and diamond grinding wheels, because of their much higher thermal conductivity in comparison with Al_2O_3 grinding wheel). The cutting fluid creates a film on the grinding grains and so eliminates strong adhesion of Ni alloy.

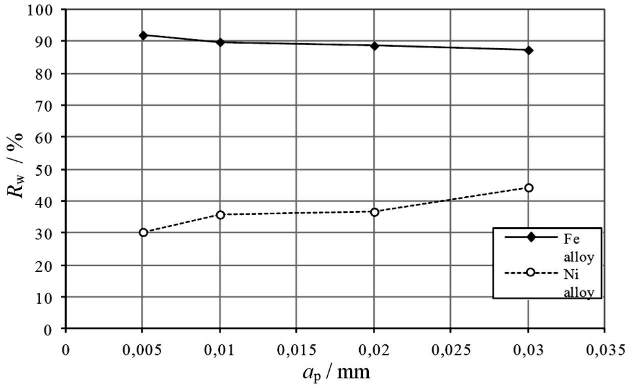

Figure 5 Energy partition R_w for Al_2O_3 grinding wheel

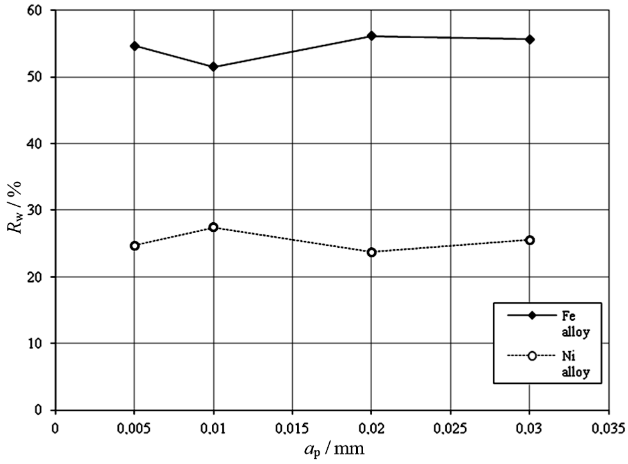

Figure 6 Energy partition R_w for diamond grinding wheel

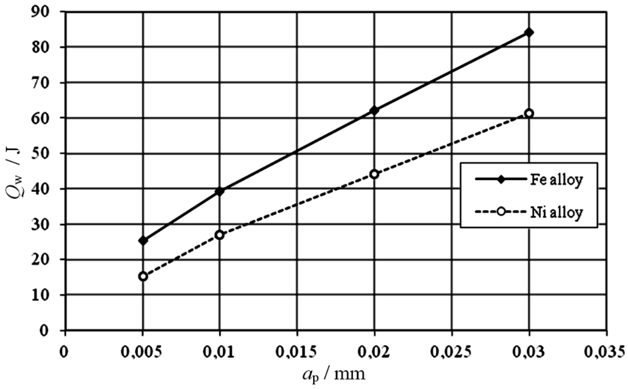

Figure 7 Heat entering the workpiece for Al_2O_3 grinding wheel (per 1 mm of grinding width)

The lower temperatures for CBN and diamond grinding wheels are not associated only with the higher thermal conductivity for CBN and diamond grains, but low thermal load has to be also associated with lower density of grains in the wheel – workpiece contact and lower friction coefficient. Figs. 3, 4 and also Figs. 7, 8 show that temperature in the cutting zone, mechanical load and the heat entering wheel (workpiece) strongly depend on cutting depth a_p. On the other hand, such parameter as energy partition R_w is less sensitive to removal rates and more stable in the whole range of the cutting depths.

Table 3 Influence of cutting fluid (Emulzín H – 2 % concentration) on the temperature in the contact of grinding wheel and workpiece, v_c = 25 m/s, v_w = 4 m/min, a_p = 0,02 mm

	Al_2O_3 / °C		CBN / °C		Diamond / °C	
	dry	Emulzín H	dry	Emulzín H	dry	Emulzín H
Fe alloy	455	275	300	180	222	167
Ni alloy	630	550	610	170	300	100

Table 4 Influence of cutting fluid (Emulzín H – 2 % concentration) on the partitioning ratio R_w, v_c = 25 m/s, v_w = 4 m/min, a_p = 0,02 mm

	Al_2O_3 / %		CBN / %		Diamond / %	
	dry	Emulzín H	dry	Emulzín H	dry	Emulzín H
Fe alloy	88	68	77	48	64	48
Ni alloy	36	25	28	8	24	9

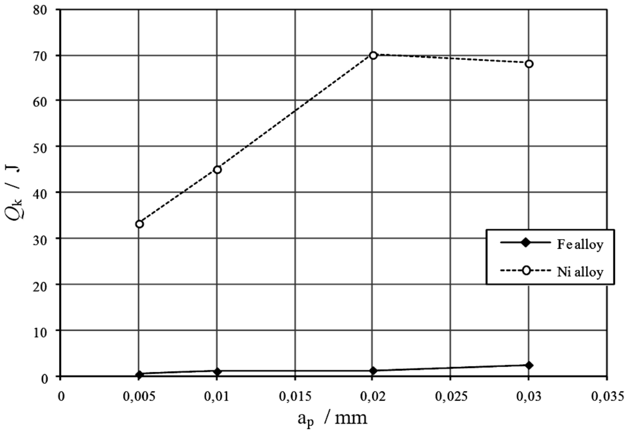

Figure 8 Heat entering the wheel for Al_2O_3 grinding wheel (per 1 mm of grinding width)

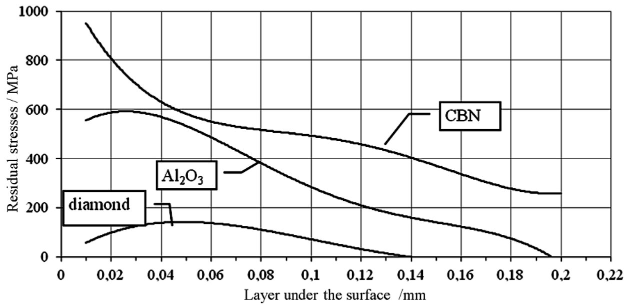

Figure 9 Residual stresses after grinding Ni alloy without cutting fluid, v_c = 25 m/s, v_w = 4 m/min, a_p = 0,02 mm

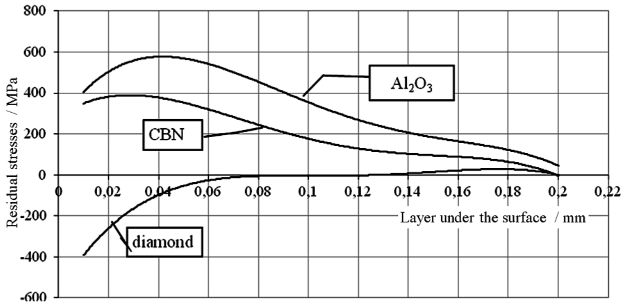

Figure 10 Residual stresses after grinding Ni alloy with cutting fluid (Emulzín H – 2 % concentration), v_c = 25 m/s, v_w = 4 m/min, a_p = 0,02 mm

Figs. 9 and 10 and also Tabs. 3 and 4 illustrate that influence of cutting fluid on the stress distribution, thermal load and heat distribution is higher for the application CBN and diamond grinding wheels than that for the application of conventional Al_2O_3 wheel. While the difference between maximum of tensile stress with and without application of cutting fluid is very low for conventional Al_2O_3 wheel, this difference is much higher for CBN and diamond wheel. The main reason can be found in elimination of thermal barrier associated with Ni alloy adhesion of the grinding grains as it was previously mentioned. The different conditions in the wheel – workpiece contact (in terms of adhesion intensity) significantly influences the heat distribution, energy dissipation and also surface integrity associated with its thermal load.

4 Conclusions

Reduction of the thermal load on the ground part significantly influences its quality represented by residual stresses, Fig. 9 and Fig. 10. Results of residual stresses measurement illustrate correlation between the partition ratio R_w and the residual stresses. Compressive residual stresses become more likely with lower values of partition ratio (smaller proportion of the energy entering the workpiece). And so CBN and diamond grinding of Ni alloy with cutting fluid enables to achieve acceptable residual stresses. On the other hand, the high costs of CBN and diamond grinding wheels limit their application. Even though the surface temperature must not exceed the working temperature for the parts made of Ni alloys, the tensile residual stresses induced at this temperature can result in appreciably lower fatigue strength due to the surface damage.

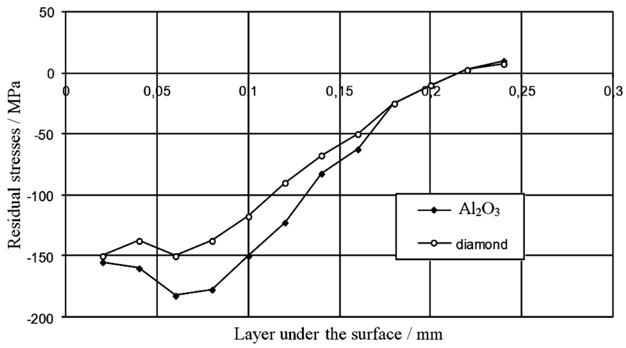

Figure 11 Residual stresses after grinding Ni alloy and the following mechanical hardening the ground surface (rolling)

For these reasons, nowadays there is a tendency to include an additional operation of mechanical hardening the ground surfaces for all parts made for the aerospace and space industry (Fig. 11). Moreover, new progressive grinding wheels are produced to eliminate adhesion of Ni alloy such as Vortex grinding wheels. The new concept of these wheels is based on high porosity. While conventional grinding wheels are produced with the maximum porosity 13 (in the special production 16) Vortex grinding wheel porosity can reach 27. The high porosity of Vortex grinding wheel and homogeneity of its distribution enable to obtain a more stable grinding process with longer dressing intervals and low thermal load of the surface [10].

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