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ROLE OF CUTTING FLUID IN MACHINING NICKEL ALLOYS

VPLYV REZNEJ KVAPALINY NA OBRÁBANIE NIKLOVÝCH ZLIATIN

Abstract

This paper deals with machining EI 698 VD nickel alloy. There is presented influence of cutting fluid application on intensity of adhesion during grinding and related aspects as the grinding forces, thermal load of ground surface and the quality of ground parts in terms of residual stresses. The heat distribution when grinding EI 698 VD nickel alloy differs from the heat distribution when grinding a conventional roll bearing steel. The more significant role takes application of cutting fluid during grinding nickel alloy in comparison with grinding a conventional roll bearing steel. 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.

Abstrakt

Článok sa zaoberá problematikou obrábania niklových zliatin. Je v ňom analyzovaný vplyv reznej kvapaliny na intenzitu adhézneho pôsobenia pri brúsení a s tým súvisiace aspekty rezného procesu ako je silové pôsobenie, tepelné zaťaženie obrobeného povrchu, tepelná bilancia ako aj kvalita obrobeného povrchu reprezentovaná predovšetkým zvyškovými napätiami. Článok poukazuje na odlišný charakter tepelnej bilancie pri brúsení niklovej zliatiny EI 698 VD v porovnaní s ložiskovou oceľou ako aj skutočnosťou, že aplikácia reznej kvapaliny pri brúsení niklových zliatin zohráva oveľa výraznejšiu úlohu ako v prípade brúsenia konvenčných materiálov. Článok taktiež poukazuje na možnosti dosiahnutia priaznivého stavu zvyškových napätí v povrchových vrstvách prostredníctvom aplikácie brúsnych kotúčov na báze KNB a diamantu ako aj aplikáciou iných technologických operácií.

1 INTRODUCTION

Nowadays, there is a strong tendency to eliminate application of cutting fluids in machining [1]. On the other hand, application of new progressive materials cause difficulties during their machining [2, 3, 4] and so elimination of cutting fluid could be more difficult. Nickel and its alloys are attractive materials due to their high strength that is maintained at elevated temperatures and their exceptional corrosion resistance. Nickel alloys are classified as difficult-to-machine materials. Machined parts made of nickel 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 nickel alloys is easily damaged during machining operations, especially during grinding. Even properly processed grinding practice using conventional parameters result in appreciably lower fatigue strength due to surface damage.

The damage of a workpiece when grinding is usually thermally induced and comes not just from the heat generated in the cutting zone, but also by the temperature on the surface of a ground part, its gradient and R_w coefficient [5] – partition ratio (the ratio of the heat entering the workpiece to the total heat). Residual tensile stresses, which are primarily thermal in origin, may be unacceptable.

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Investigation has found that preferred compressive stresses are more likely to be achieved with CBN and diamond grinding wheels. Results of investigations [5] 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 roll bearing steels using an alumina grinding wheel. [4, 5] This is given by kinematics conditions and the fact that the thermal conductivity of conventional roll bearing steels (46 $W.m^{-1}.K^{-1}$) is higher than alumina grinding wheel (6÷30 $W.m^{-1}.K^{-1}$, wide range of the presented values). The heat distribution when grinding a EI 698 VD nickel alloy differs from the heat distribution when grinding conventional roll bearing steels because of poor thermal properties of nickel alloys (thermal conductivity of nickel alloys is 12,5 $W.m^{-1}.K^{-1}$) and so this paper deals with its analysis and relation to quality of the ground parts represented in terms of residual stresses.

2 EXPERIMENTAL METHOD

Experimental analysis of heat distribution is based on "Moving Heat Source Theory" (Jaeger [6]). 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 center of the heat source. A two-dimensional, steady-state temperature distribution for this model is obtained as

$$\theta\frac{\pi k v_w}{2q\alpha} = \int_{X-L}^{X+L} e^{-u} K_o \left\{ \left(Z^2 + u^2 \right)^{0.5} \right\} du \tag{1}$$

where:

θ . temperature rise above ambient $\left[{}^oC \right]$,

α . thermal diffusivity $\left[\frac{m^2}{s^{-1}} \right]$,

k .. thermal conductivity $\left[\frac{W}{m^{-1}.K^{-1}} \right]$,

q .. heat flux $\left[\frac{kg.m^2}{s^{-1}} \right]$,

l .. half length of band source $\left[m \right]$,

K_0 the modified Bessel function,

u .. specific grinding energy $\left[\frac{J}{m^{-3}} \right]$,

X, Z, L – dimensionless quantities ($X=v_w*x/2\alpha$, $Z= v_w*z/2\alpha$, $L= v_w*l/2\alpha$).

$$\theta \frac{\pi k v_w}{2 R_w q \alpha} = 3.1 L^{0.53} \exp\left(-0.69 L^{-0.37} Z\right) \qquad (2)$$

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

$$\theta_d = 0.947 \alpha^{0.47} k^{-1} F_c R_w v_c v_w^{-0.47} l_c^{-0.47} \qquad (3)$$

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

where:

F_c tangential force component $[N]$,

v_c .. wheel speed $\left[\frac{m}{s^{-1}}\right]$,

l_c . contact length $[m]$.

F_c*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) [7].

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 introduced by Peklenik [8] and improved by Gu and Wager (both quantities measured through an A/D card to a PC).

Cutting conditions: v_c = 25m.s^{-1}, v_w = 4m.min^{-1},

grinding wheel A99 60LVS,

surface plunge grinding,

without and with cutting fluid (Emulzín H 2 % concentration).

Machined materials:

- ☐ nickel alloy EI 698VD - thermal diffusivity 3,62 m^2.s^{-1}, Rm = 1100 MPa at 500 °C, R_m= 1050 MPa at 700 °C, R_m= 700 MPa at 800 °C, R_p = 720 MPa at 500 °C, A = 26 % at 500 °C, Z = 35% at 500 °C, 363 HB,
- ☐ hardened roll bearing steel 14 209.4 (100CrMn6) (62HRC) - thermal diffusivity 12,4*10^{-6} m^2.s^{-1}, workpieces 50x25x10 mm.

3 EXPERIMENTAL RESULTS

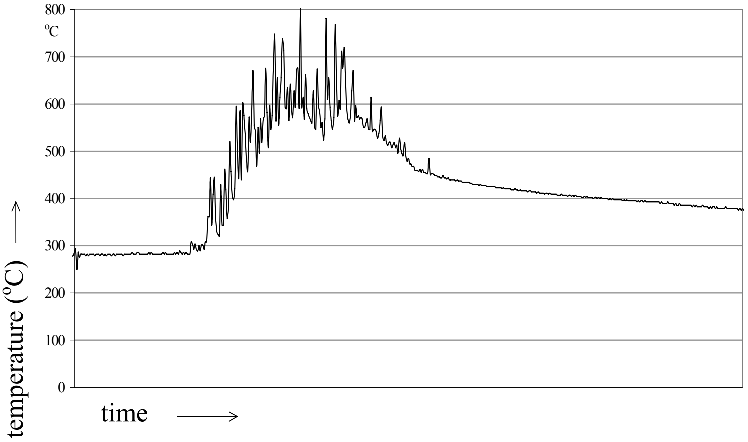

Fig. 1 Typical measured temperature rise when grinding 14 209.4 (a_p = 0, 03 mm)

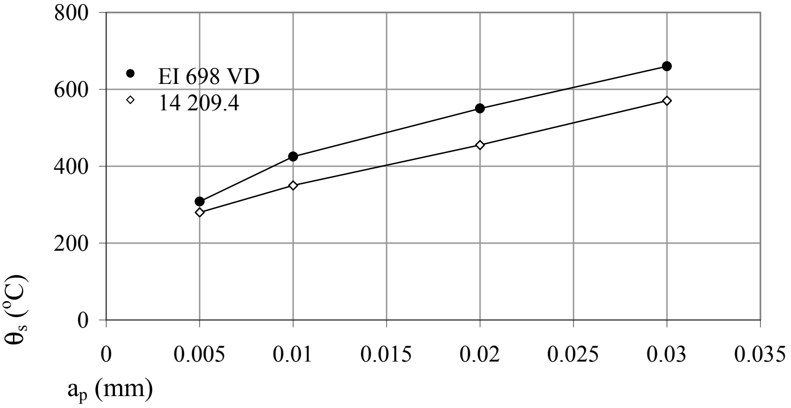

Fig. 2 Surface temperature for hardened roll bearing steel 14 209.4 and EI 698 VD nickel alloy

The temperature on the surface θ_s was obtained by putting a smooth curve through the measured trace (Fig. 1). Fig. 2 presents a relation between surface temperature and the cutting depth. The total heat was determined by measuring a tangential force and wheel speed (Fig. 3). The partitioning ratio R_w (Fig. 4) is the portion of the heat entering the workpiece to the total heat calculated by substituting the maximum temperature rise θ_s from Fig. 2 and the tangential grinding force F_c from Fig. 3 into equation (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. On the basis of this assumption the maximum heat entering the grinding chips is about 8% for 14 209.4 and abut 6 % for nickel alloy.

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 say 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. 4). The high mechanical and thermal load of grains when grinding the nickel alloy leads to a high grain wear rate, low *G* ratios and the strong adhesion between the machined material and the cutting grain [4]. The maximum temperature rise for nickel alloy is much higher than that of the roll bearing steel, although the net energy input for the nickel alloy is lower than for the hardened steel (Fig. 6). This is because the thermal conductivity of the nickel 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 nickel 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 EI698 VD nickel alloy. The surface temperatures for the CBN and diamond grinding wheels (except dry grinding of nickel 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. 1. Next, the values of the partitioning ratios are much lower with CBN and diamond grinding and the use of cutting fluid, Tab. 2 and Fig. 5. Nickel alloy adheres to the grinding grains and so 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 nickel alloy.

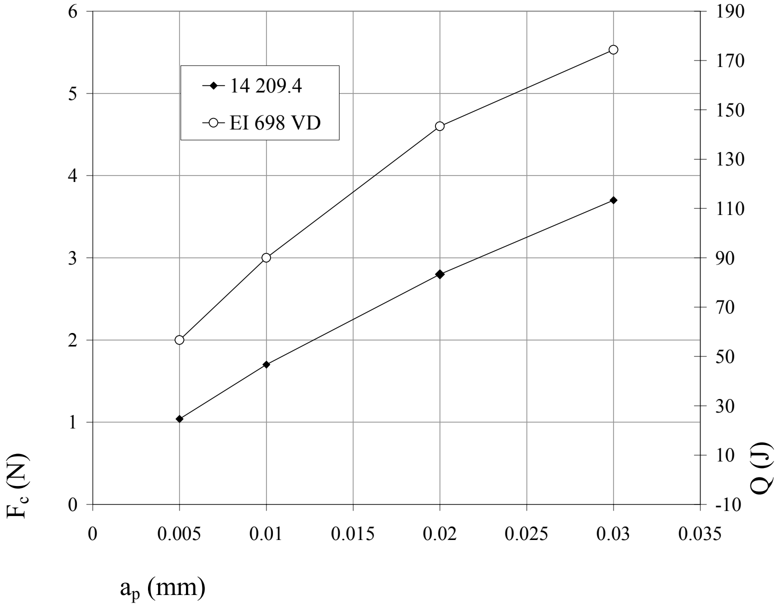

Fig. 3 Total heat Q and tangential component of grinding force F_c per 1 mm of grinding width

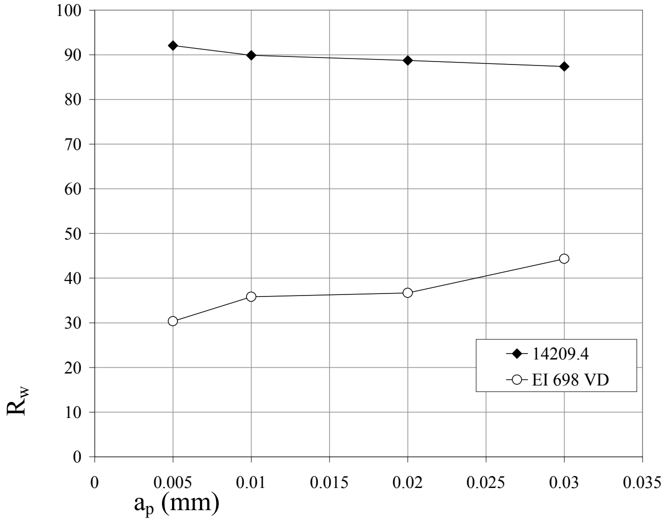

Fig. 4 Energy partition R_w for Al_2O_3 grinding wheel

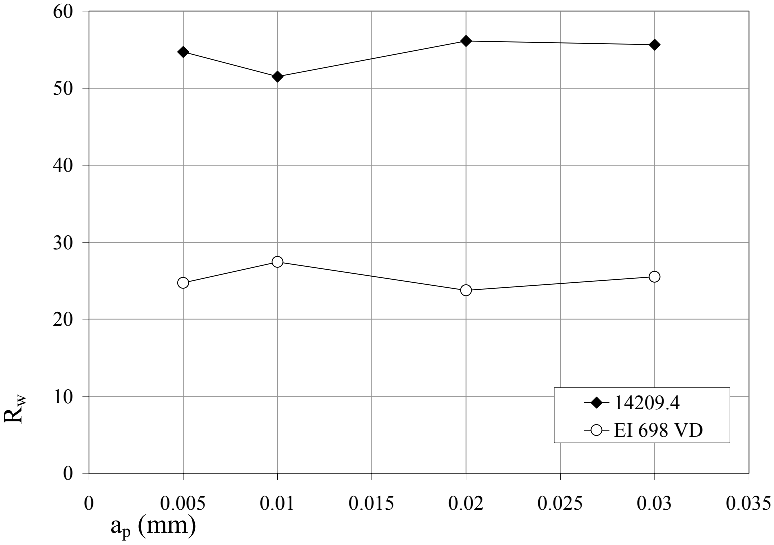

Fig. 5 Energy partition R_w for diamond grinding wheel

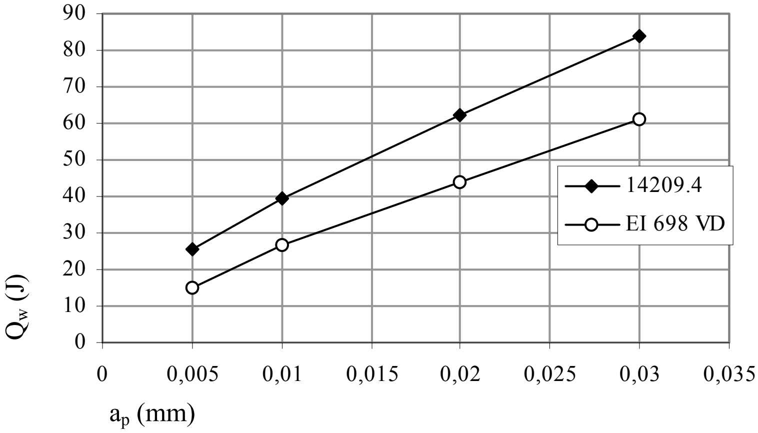

Fig. 6 Heat entering the workpiece for Al_2O_3 grinding wheel (per 1 mm of grinding width)

Tab. 1 Influence of cutting fluid (Emulzín H – 2 % concentration) on the temperature in the contact of grinding wheel and workpiece, $v_c = 25$ m.s^{-1}, $v_w = 4$ m.min^{-1}, $a_p = 0{,}02$ mm

θ_s	Al_2O_3 (°C)		CBN (°C)		Diamant (°C)	
	dry	wet	dry	wet	dry	wet
14 209.4	455	275	300	180	222	167
EI 698 VD	550	630	610	170	300	100

Tab. 2 Influence of cutting fluid (Emulzín H – 2 % concentration) on the partitioning ratio Rw, vc = 25 m.s-1, vw = 4 m.min-1, ap = 0,02 mm

R_w	Al_2O_3 (%)		CBN (%)		Diamant (%)	
	dry	wet	dry	wet	dry	wet
14 209.4	88	68	77	48	64	48
EI 698 VD	36	25	28	8	24	9

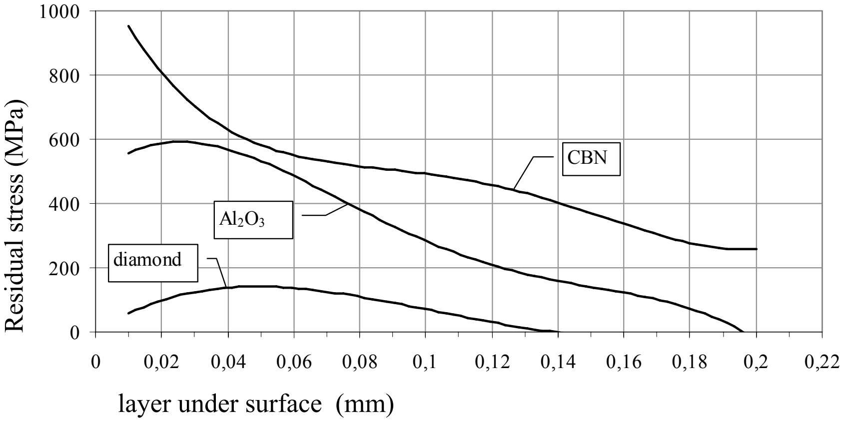

Fig. 7 Residual stresses after grinding the EI 698 VD nickel without cutting fluid, $v_c = 25$ m.s^{-1}, $v_w = 4$ m.min^{-1}, $a_p = 0{,}02$ mm

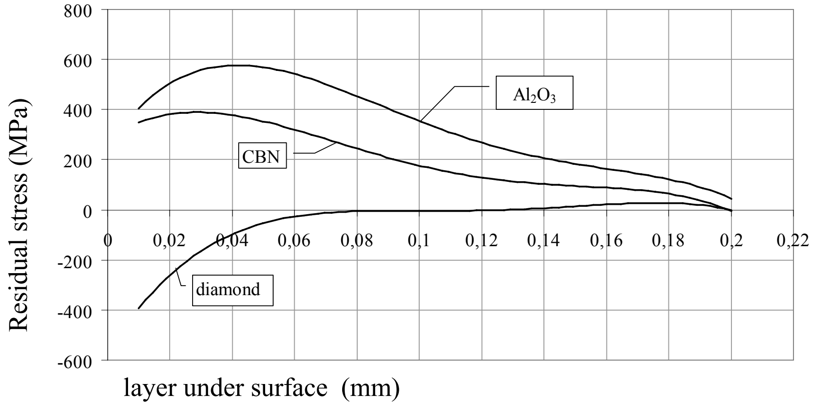

Fig. 8 Residual stresses after grinding the EI 698 VD nickel alloy with cutting fluid (Emulzín H – 2 % concentration), $v_c = 25$ m.s^{-1}, $v_w = 4$ m.min^{-1}, $a_p = 0{,}02$ mm

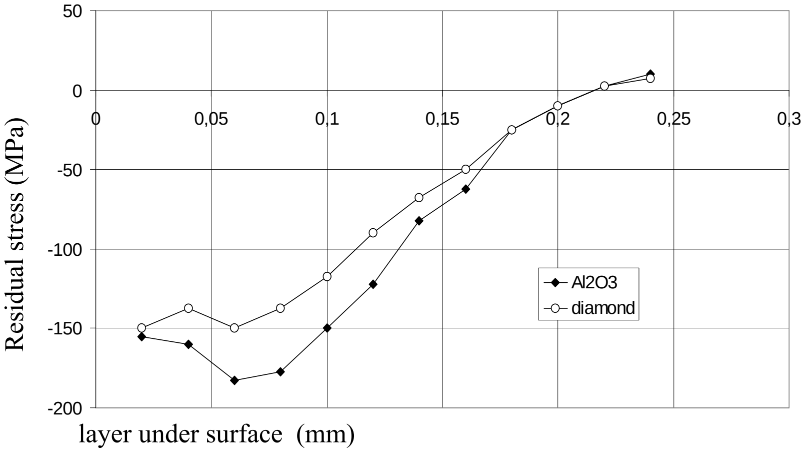

Fig. 9 Residual stresses after grinding the EI 698 VD nickel alloy and the following mechanical hardening the ground surface (rolling)

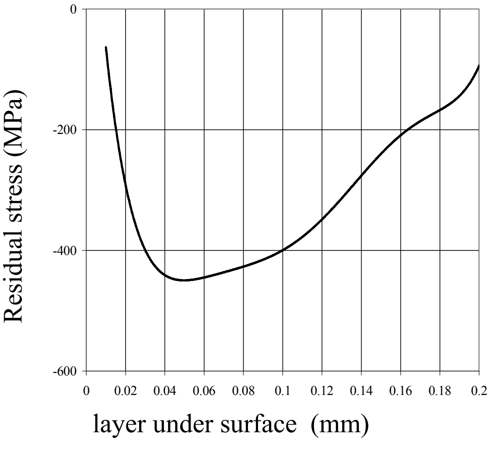

Fig. 10 Residual stresses after face milling the EI 698 VD nickel alloy , $v_c = 20$ m.min^{-1}, $a_p = 2$ mm, $f_z = 0{,}1$ mm [4]

4 CONCLUSIONS

Reducing the thermal load on the ground part significantly influences their quality represented by residual stresses, Fig. 7 and Fig. 8. Results of the measurement of residual stresses show that there is a strong correlation between the partition ratio R_w and the residual stresses. Compressive residual stresses become more likelihood with lower values of partition ratio (smaller proportion of the energy entering the workpiece). And so CBN and diamond grinding of EI 698VD nickel 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 thought the surface temperature must not exceed the working temperature for the parts made of nickel alloys, the tensile residual stresses induced at this temperature can result in appreciably lower fatigue strength due to the surface damage.

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.9). Moreover, application the different strategy of technology enables to reach the compressive state of residual stresses (for example, application of face milling operation ensures low surface roughness [4] and suitable residual stresses in the machined surface, Fig. 10).

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