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Analiza porazdelitve toplote pri brušenju titanove zlitine VT 9 in njena povezava do zaostalih napetosti

Analysis of the Heat Distribution when Grinding of a VT 9 Titanium Alloy and its Relation to Residual Stresses

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Porazdelitev toplote pri strojni obdelavi je ena od fenomenoloških značilnosti tega postopka, ker pomembno vpliva na funkcionalne lastnosti obdelanih površin. Prispevek obravnava porazdelitev toplote pri brušenju titanove zlitine VT 9 in njeno razmerje do kakovosti brušenih delov, ki jo predstavljajo zaostale napetosti. Analiza porazdelitve toplote temelji na merjenju temperature na stiku brusa in obdelovanca ter obodne komponente rezalne sile. Porazdelitev toplote pri brušenju titanove zlitine VT 9 se razlikuje od porazdelitve toplote pri brušenju običajnega jekla za kotalne ležaje (14 209.4), kot tipičnega predstavnika brušenih kaljenih jekel in sicer predvsem zaradi majhne toplotne prevodnosti titanijevih zlitin. Nadalje, uporaba CBN in diamantnih brusov znatno zmanjša izpostavljenost brušenih delov toploti, predvsem kadar se uporablja hladilno-mazalna tekočina. To dejstvo pomembno vpliva na zaostale napetosti po brušenju. Rezultati analize kažejo, da obstaja močna povezava med porazdelitvijo energije in zaostalimi napetostmi.

(Ključne besede: brušenje, zlitine titana, porazdelitve toplote, zaostale napetosti)

Heat distribution during machining is one of the phenomenological characteristics of this process because it significantly influences the functional properties of machined surfaces. This paper deals with heat distribution during the grinding of a VT 9 titanium alloy and its relationship to the quality of ground parts in terms of residual stresses. The analysis of the heat distribution is based on a measurement of the temperature in the contact of the grinding wheel and workpiece, and the tangential component of the cutting force. The heat distribution when grinding a VT 9 titanium alloy differs from the heat distribution when grinding a conventional (14 209.4) roll-bearing steel (a typical representative of ground-hardened steels) mainly because of the low heat conductivity of titanium alloys. Also the application of CBN and diamond grinding wheels significantly reduces 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 a strong correlation between energy partitioning and residual stresses.

(Keywords: grinding, titanium alloys, heat distributions, residual stresses)

0 UVOD

Titan in njegove zlitine so priljubljeni materiali zaradi njihovega edinstvenega velikega razmerja med trdnostjo in težo, ki se ohranja pri zvišanih temperaturah ter zaradi njihove izjemne odpornosti proti koroziji. Titanove zlitine se uvrščajo med težko obdelovane materiale. Strojno obdelani deli iz titanovih zlitin so običajno izpostavljeni utrujanju, kajti najpogosteje se titan uporablja v letalski in vesoljski industriji za ogrodja letal in komponente motorjev. Fine operacije strojne obdelave imajo običajno za posledico nihajno utrujenostno trdnost, ki je mnogo večja (do približno 5-krat) kakor pri ustreznih neugodnih rezalnih razmerah [1]. Kahles idr. [2] trdijo, da se površina titanovih zlitin zlahka

0 INTRODUCTION

Titanium and its alloys are attractive materials due to their very high strength-to-weight ratio, which is maintained at elevated temperatures. and their exceptional corrosion resistance. Titanium alloys are classified as difficult-to-machine materials. The machined parts made from titanium alloys are usually exposed to the fatigue load because the major applications of titanium have been in the aerospace industry, where titanium is used in airframes and engine components. Gentle machining operations usually result in a high cyclic fatigue strength that is much higher (as much as five times) than that of the corresponding unfavourable cutting conditions [1]. Kahles et al. [2] claim that the surface of titanium poškoduje med postopki strojne obdelave, zlasti med brušenjem. Celo ustrezna praksa brušenja z uporabo običajnih parametrov ima za posledico znatno nižjo utrujenostno trdnost zaradi poškodb površine.

Poškodbe obdelovanca pri brušenju so običajno termično povzročene, in sicer ne samo zaradi toplote, nastale v coni rezanja, ampak tudi zaradi temperature na površini brušenega dela, njenega gradienta in koeficienta R_w- razmerja porazdelitve (razmerje med toploto, ki vstopi v obdelovanec in celotno toploto). Zaostale natezne napetosti, ki so termičnega izvora, so lahko nesprejemljive. Pri raziskavah je bilo ugotovljeno, da se ugodne tlačne napetosti bolj verjetno dosežejo z brusi CBN in diamantnimi brusi. Rezultati raziskav [3] kažejo, da je ugodneje uporabiti bruse CBN in diamantne bruse, pri katerih je vstop energije v obdelovanec manjši. Razmerje porazdelitve je zato koristen pokazatelj učinkovitosti brusa glede na verjetnost nateznih napetosti.

Pri brušenju običajnih jekel za kotalne ležaje in pri uporabi brusa iz korunda večina energije vstopa v obdelovanec (90%) ([3] in [4]). To je podano s kinematičnimi pogoji in z dejstvom, da je toplotna prevodnost običajnih ležajnih jekel (46 W/mK) večja kot toplotna prevodnost brusa iz korunda (6÷30 W/mK, veliko področje podanih vrednosti). Porazdelitev toplote pri brušenju titanove zlitine VT 9 se razlikuje od porazdelitve toplote pri brušenju običajnih jekel za kotalne ležaje, zaradi slabih termičnih lastnosti titanovih zlitin (toplotna prevodnost titanovih zlitin je 7,5 W/mK) in zato ta prispevek obravnava analizo toplotne porazdelitve in njeno razmerje do kakovosti brušenih delov, ki je odvisno od zaostalih napetosti.

1 EKSPERIMENTALNA METODA

Eksperimentalna analiza porazdelitve toplote temelji na ‘’teoriji pomičnega vira toplote” [5]. Vir toplote s stalnim tokom toplote na enoto površine *q*, dolžino 2*l*, se premika vzdolž površine polneskončnega mirujočega telesa z nespremenljivo hitrostjo v_w. Izhodišče koordinatnih osi *x*, *z* je v središču izvora toplote. Dobimo dvorazsežno, ustaljeno porazdelitev toplote:

alloys is easily damaged during machining operations, especially during grinding. Even proper grinding practice using conventional parameters results in an appreciably lower fatigue strength due to surface damage.

The damage to 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 (the 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. Investigations have found that 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 the energy enters the workpiece (90%) when grinding conventional roll-bearing steels using an alumina grinding wheel ([3] and [4]). This is given by kinematics conditions and the fact that the thermal conductivity of conventional roll-bearing steels (46 W/mK) is higher than that the alumina grinding wheel (6÷30 W/mK, wide range of the presented values). The heat distribution when grinding a VT 9 titanium alloy differs from the heat distribution when grinding conventional roll-bearing steels because of the poor thermal properties of titanium alloys (the thermal conductivity of titanium alloys is 7.5 W/mK) and so this paper deals with its analysis and the relation to quality of the ground parts in terms of residual stresses.

1 EXPERIMENTAL METHOD

The experimental analysis of the heat distribution is based on the “Moving Heat Source Theory” [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 the coordinate axes *x, z* is at the centre of the heat source. The two-dimensional, steady-state temperature distribution for this model is:

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

kjer pomenijo:

θ – dvig temperature nad temperaturo okolice v C°,
α – termično difuzivnost v m^2/s,
k – toplotno prevodnost v W/mK,
q – toplotni tok v m^{2}kg/s,
l – polovično dolžino območja izvora v m,
K_0 – modificirano Bessel-ovo funkcijo,
u – specifično energijo brušenja v J/m^3,
X, Z, L – brezrazsežne vrednosti ($X=v_w \cdot x/2\alpha$, $Z=v_w \cdot z/2\alpha$, $L=v_w \cdot l/2\alpha$).

where:

θ – temperature rise above ambient temperature (°C),
α – thermal diffusivity (m^2/s),
k – thermal conductivity (W/mK),
q – heat flux (m^{2}kg/s),
l – half length of the band source (m),
K_0 – the modified Bessel function,
u – specific grinding energy (J/m^3),
X, Z, L – dimensionless quantities ($X=v_w \cdot x/2\alpha$, $Z=v_w \cdot z/2\alpha$, $L=v_w \cdot l/2\alpha$).

Takazawa je dobil rešitev za enačbo (1) z numerično integracijo. Njena poenostavljena oblika je:

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

$$\theta \frac{\pi k v_w}{2 R_w q \alpha} = 3.1 L^{0.53} \exp(-0,69 L^{-0,37} Z) \tag{2}$$

in enačba za največji dvig temperature θ_d (z=0) je:

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

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

kjer pomenijo:
F_c – obodno komponento sile v N,
v_c – hitrost brusa v m/s,
l_c – dolžino dotika v m.

$F_c \cdot v_c$ je skupna energija, ustvarjena v področju rezanja *Q*. Porazdelitev energije R_w se lahko izračuna tako, da vstavimo največji dvig temperature θ_d in obodno silo brušenja F_c v enačbo (3).

Meritev vrednosti F_c je bila izvedena s piezoelektričnim merilnikom sile KISTLER skupaj z meritvijo temperature. Temperatura je bila izmerjena z metodo termoelementa (sl. 1), ki jo je uvedel Peklenik [6] in ki sta jo izboljšala Gu in Wager [7] (obe vrednosti sta bili merjeni z uporabo kartice A/D na osebnem računalniku).

Rezalne razmere: v_c = 25 m/s, v_w = 4 m/min, brus A99 60LVS, profilno brušenje, s hladilno mazalno tekočino in brez nje (Emulzin z 2 % koncentracijo).

Strojno obdelani materiali:

1. titanova zlitina VT 9 – termična difuzivnost $2,87 \cdot 10^{-6}$ m²/s, meja plastičnosti R_m = 900 MPa po žarjenju. Sestava zlitine VT 9 je iz faze α in β. Njena kemična sestava je podana v preglednici 1.
2. Kaljeno jeklo za kotalne ležaje (14 209.4) – termična difuzivnost $12,4 \cdot 10^{-6}$ m²/s. Kemična sestava je podana v preglednici 2.

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

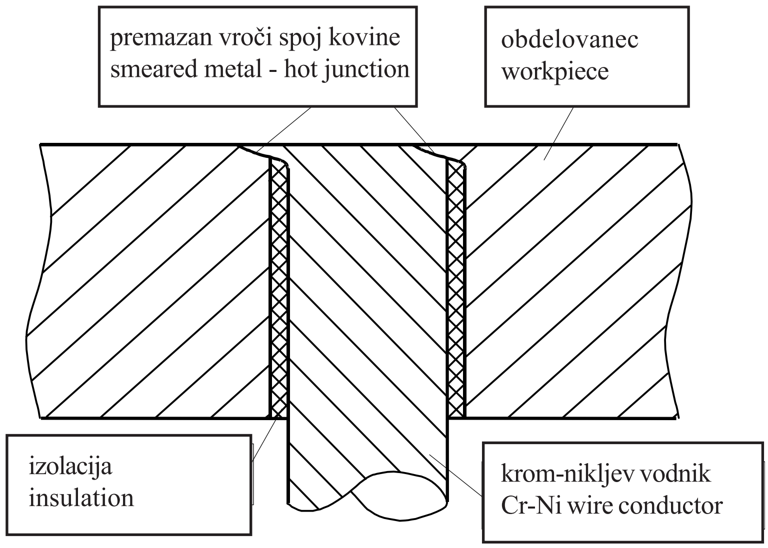
$F_c \cdot v_c$ is the total energy created in the cutting zone *Q*. The energy partition R_w can be calculated by entering the maximum temperature rise θ_d and the tangential grinding force F_c into equation (3).

The measurement of F_c was made with a piezoelectric KISTLER dynamometer together with the measurement of temperature. The temperature was measured with 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, plane plunge grinding, with and without cutting fluid (Emulzín 2 % concentration).

Machined materials:

1. VT 9 titanium alloy - thermal diffusivity $2.87 \cdot 10^{-6}$ m²/s, yield strength R_m = 900 MPa, after annealing. The structure of VT9 consists of α and β phase. Its chemical composition is given in Table 1.
2. hardened roll-bearing (14 209.4) steel - thermal diffusivity $12,4 \cdot 10^{-6}$ m²/s. Its chemical composition is given in Table 2.



Sl. 1. *Peklenikova metoda za merjenje temperature na stiku brusa in obdelovanca*

Fig.1 *Peklenik method for the measurement of the temperature in the contact of the grinding wheel and the workpiece*

Preglednica 1. *Kemična sestava titanove zlitine VT 9*
Table 1. *Chemical composition of the VT 9 titanium alloy*

element	Al	Mn	Si	Zr	O_2	N_2	H_2	C	Fe
%	5,8-7	2,8-3,8	0,2-0,3	0,8-2,5	$\leq$ 0,15	$\leq$ 0,05	$\leq$ 0,015	$\leq$ 0,1	$\leq$ 0,25

Preglednica 2. *Kemična sestava jekla za kotalne ležaje (14 209.4)*
Table 2. *Chemical composition of the hardened roll-bearing (14 209.4) steel*

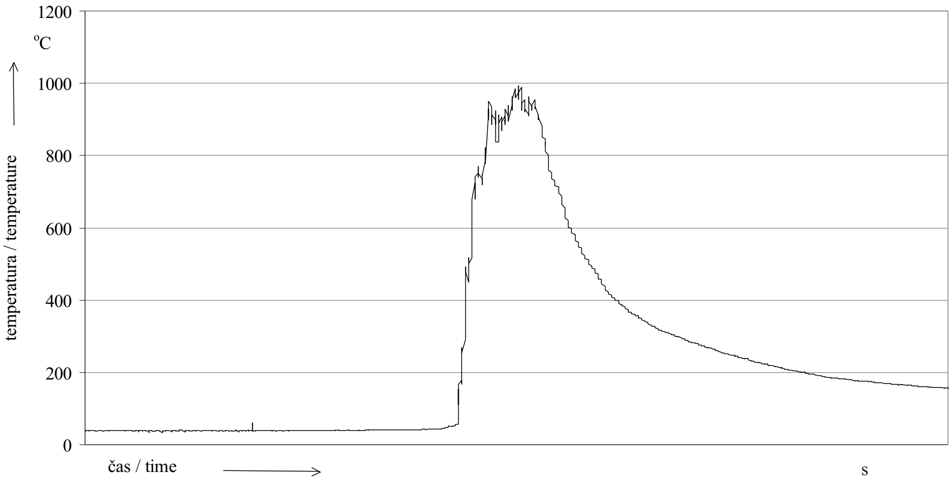
element	Cr	Mn	Si	Cu	S	P	Ni	C
%	1,3-1,6	0,9-1,2	0,3-0,6	$\leq$ 0, 25	$\leq$ 0, 03	$\leq$ 0, 03	$\leq$ 0, 3	1

2 EKSPERIMENTALNI REZULTATI

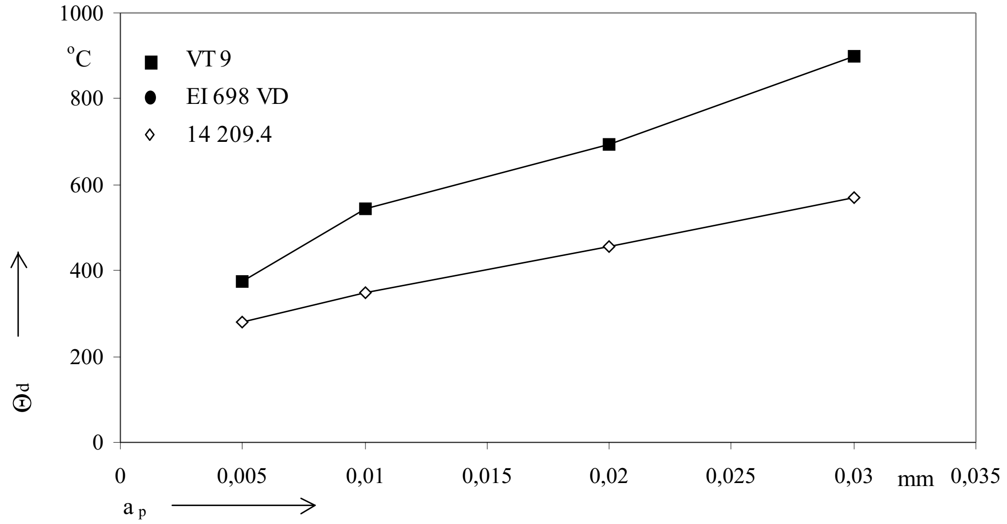
Temperaturo na površini θ_d smo dobili tako, da smo dali gladko krivuljo skozi merjeno območje. Slika 3 kaže odnos med temperaturo površine in globino rezanja. Skupna toplota je ugotovljena tako, da smo izmerili obodno silo in hitrost koluta (sl. 4).

2 EXPERIMENTAL RESULTS

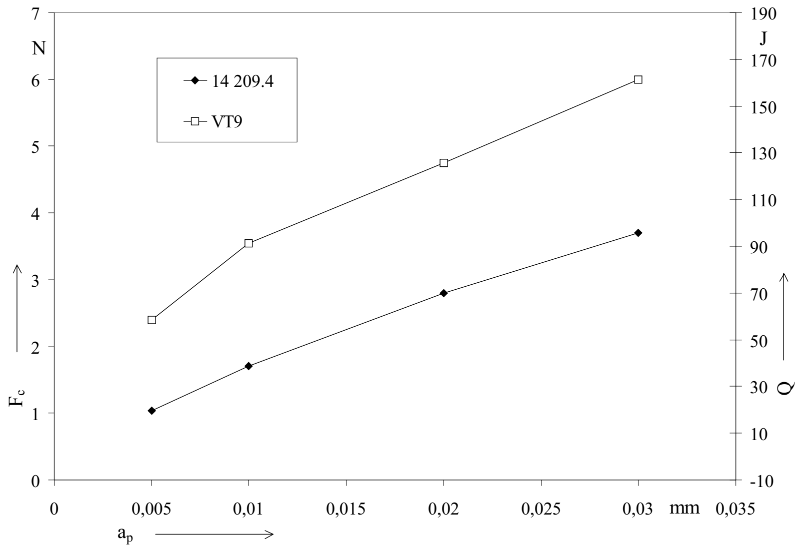
The temperature on the surface, θ_d, was obtained by putting a smooth curve through the measured trace. Figure 3 presents the relation between the surface temperature and the cutting depth. The total heat was determined by measuring the tangential force and the wheel speed (Figure 4).



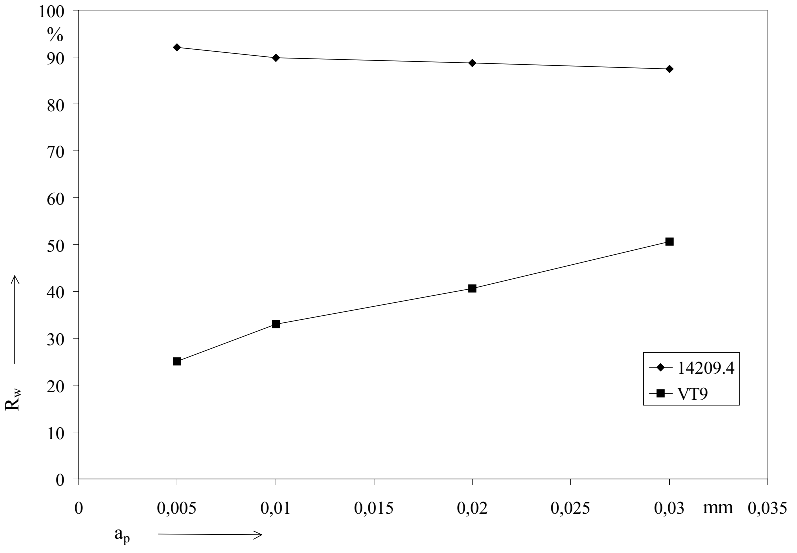
Sl. 2. *Tipični izmerjeni dvig temperature pri brušenju titanove zlitine VT 9* (a_p = 0,03 mm)
Fig.2. *Typical measured temperature rise when grinding the VT 9 titanium alloy* (a_p = 0.03 mm)



Sl. 3. *Temperatura površine kaljenega jekla za kotalne ležaje 14 209.4 in titanove zlitine VT 9*
Fig. 3. *Surface temperature for the hardened roll-bearing 14 209.4 steel and the VT 9 titanium alloy*



Sl. 4. *Skupna toplota Q in obodna komponenta brusne sile F_c na 1 mm širine brušenja*
Fig. 4. *Total heat, Q, and tangential component of grinding force, F_c, per 1mm of grinding width*



Sl. 5. *Razmerje porazdelitve R_w*
Fig. 5. *Partition Ratio R_w*

Razmerje porazdelitve R_w (sl. 5) je delež toplote, ki vstopi v obdelovanec, proti celotni toploti, ki jo izračunamo tako, da vstavimo največji dvig temperature θ_d s slike 3 in obodno silo brušenja F_c s slike 4 v enačbo (3).

Pri postopku brušenja se skoraj vsa energija brušenja spremeni v toploto na majhnem območju brušenja. Pri suhem brušenju so trije pomembni toplotni ponori: obdelovanec, brus in odrezki. Največja mogoča toplota, ki vstopi v odrezke, se lahko izrazi z specifično odstranitvijo kovine, gostoto, specifično toplotno kapaciteto in razliko med temperaturo taljenja in temperaturo okolice [8]. Na temelju te predpostavke je največja toplota, ki vstopi v odrezke, približno 8 % pri 14 209.4 in približno 4,5 % pri titanovi zlitini. Velik del nastale toplote preide v obdelovanec, kar ima

The partitioning ratio R_w (Figure 5) is the ratio of the heat entering the workpiece to the total heat, calculated by entering the maximum temperature rise, θ_d, from Figure 3 and the tangential grinding force, F_c, from Figure 4 into equation (3).

In a 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: the workpiece, the grinding wheel and the grinding chips. The maximum possible heat entering the grinding chips can 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 14 209.4 and about 4.5% for the titanium alloy. A large part of the generated heat flows into the workpiece, which za posledico skrajno visoke temperature na stiku med brusom in obdelovancem.

Na podlagi eksperimentalnih rezultatov je mogoče trditi, da majhen delež energije vstopi v brus pri brušenju kaljenega jekla. Pri brušenju titanove zlitine v brus vstopi približni 65 % toplote. Velika mehanska in termična obremenitev zrn pri brušenju titanove zlitine vodi do velike obrabe zrn in močne adhezije med obdelovanim materialom in rezalnim zrnom [9]. Največji dvig temperature pri titanovi zlitini je mnogo večji kakor pri ležajnem jeklu, čeprav je čisti vnos energije pri titanovi zlitini manjši kakor pri kaljenem jeklu. To je zato, ker je toplotna prevodnost titanove zlitine mnogo manjša kakor pri kaljenem jeklu (koncentracija toplote na stiku brusa in obdelovanca pri brušenju titanove zlitine).

Rezultati naslednjih preskusov kažejo, da uporaba diamantnih brusov in brusov CBN omogoča, da zmanjšamo nagnjenje k termičnim poškodbam brušenih površin na delih iz titanove zlitine VT 9. Temperature površine pri brusih CBN in diamantnih brusih, izmerjene z isto metodo, so znatno nižje od temperature površine, izmerjene pri Al_2O_3, in sicer predvsem pri uporabi hladilno mazalne tekočine (Emulzin H z 2-odstotno koncentracijo), pregl. 3. Nadalje, vrednosti porazdelitvenih razmerij so mnogo nižje pri brusih CBN in diamantnih brusih ter pri uporabi hladilno mazalne tekočine, pregl. 4. Titanova zlitina se oprime brusnih zrn in tako ustvari močno oviro za prenos toplote (predvsem pri uporabi brusov CBN in diamantnih brusov, zaradi njihove mnogo večje termične prevodnosti v primerjavi z brusom iz Al_2O_3). Hladilno mazalna tekočina ustvari film na brusnih zrnih in tako prepreči močno adhezijo titanove zlitine.

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 when grinding hardened steel. On the other hand, about 65% of the heat is entering the grinding wheel when grinding the titanium alloy. The high mechanical and thermal load of the grains when grinding the titanium alloy leads to a high grain-wear rate and strong adhesion between the machined material and the cutting grain [9]. The maximum temperature rise for the titanium alloy is much higher than that of the roll-bearing steel, although the net energy input for the titanium alloy is lower than for the hardened steel. This is because the thermal conductivity of the titanium alloy is much smaller than that of the hardened steel (the concentration of heat in the contact of the grinding wheel and the workpiece when grinding the titanium alloy).

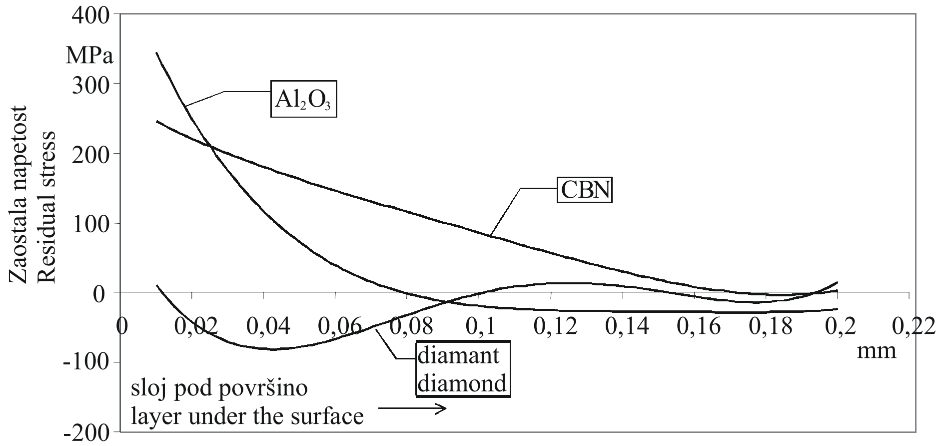
The results of the next experiments show that the use of diamond and CBN grinding wheels reduces the tendency to induce thermal damage to the ground surfaces of parts made from the VT 9 titanium alloy. The surface temperatures for the CBN and diamond grinding wheels, measured with the same technique, are significantly lower than those measured for Al_2O_3, primarily when applying cutting fluid (Emulzin H 2 % concentration), Table 3. Next, the values of the partitioning ratios are much lower with CBN and diamond grinding and the use of cutting fluid, Table 4. Titanium alloy adheres to the grinding grains and so creates a strong barrier against heat transfer (mainly when using CBN and diamond grinding wheels, because of their much higher thermal conductivity in comparison with an Al_2O_3 grinding wheel). The cutting fluid creates a film on the grinding grains and so eliminates the strong adhesion of titanium alloy.

Preglednica 3. *Vpliv hladilno mazalne tekočine (Emulzin H - 2 % koncentracijo) na temperaturo na stiku brusa in obdelovanca, $v_c = 25$ m/s, $v_w = 4$ m/min, $a_p = 0{,}02$ mm*
Table 3. *The influence of cutting fluid (Emulzin H – 2 % concentration) on the temperature in the contact of the grinding wheel and the workpiece, $v_c = 25$ m/s, $v_w = 4$ m/min, $a_p = 0.02$ mm*

	Al_2O_3 °C		CBN °C		Diamant / Diamond °C	
	suho / dry	Emulzin H	suho / dry	Emulzin H	suho / dry	Emulzin H
14 209.4	455	275	300	180	222	167
VT 9	695	580	610	235	340	180

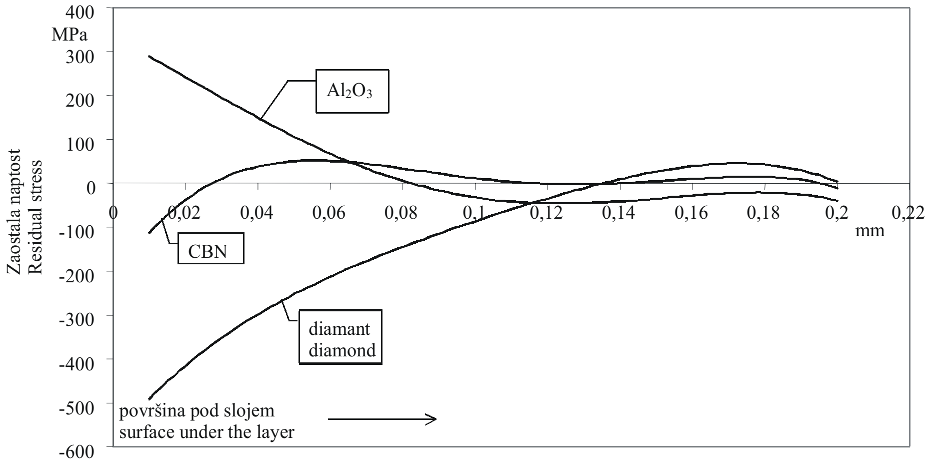
Preglednica 4. *Vpliv hladilno-mazalne tekočine (Emulzin H - 2 % koncentracijo) na razmerje porazdelitve R_w, $v_c = 25$ m/s, $v_w = 4$ m/min, $a_p = 0{,}02$ mm*
Table 4. *Influence of cutting fluid (Emulzin H – 2 % concentration) on the partitioning ratio R_w, $v_c = 25$ m/s, $v_w = 4$ m/min, $a_p = 0.02$ mm*

	Al_2O_3 %		CBN %		Diamant / Diamond %	
	suho / dry	Emulzin H	suho / dry	Emulzin H	suho / dry	Emulzin H
14 209.4	88	68	77	48	64	48
VT 9	40	38	33	12	29	19



Sl. 6. *Zaostale napetosti po brušenju titanove zlitine VT 9 brez uporabe hladilno mazalne tekočine,* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0,02 mm*

Fig. 6. *Residual stresses after grinding the VT 9 titanium alloy without cutting fluid,* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0.02 mm*



Sl. 7. *Zaostale napetosti po brušenju titanove zlitine VT 9 z uporabo hladilno mazalne tekočine (Emulzin H - 2 % koncentracijo),* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0,02 mm*

Fig. 7. *Residual stresses after grinding the VT 9 titanium alloy with cutting fluid (Emulzin H – 2 % concentration),* v_c *= 25 m/s,* v_w *= 4 m/min,* a_p *= 0.02 mm*

Zmanjšanje termične obremenitve brušenega dela znatno vpliva na njegovo kakovost, ki jo predstavljajo zaostale napetosti (sl. 6 in 7).

Rezultati merjenja zaostalih napetosti kažejo, da obstaja močna zveza med razmerjem porazdelitve R_w in zaostalimi napetostmi. Tlačne zaostale napetosti so postale bolj verjetne pri nižjih vrednostih razmerja porazdelitve R_w (manjši delež energije vstopi v obdelovanec). Tako brušenje titanove zlitine VT 9 z brusi CBN in diamantnimi brusi ter z uporabo hladilno-mazalne tekočine omogoča, da dosežemo sprejemljive zaostale napetosti. Po drugi strani pa visoki stroški brusov CBN in diamantnih brusov omejujejo njihovo uporabo. Čeprav temperatura površine ne sme presegati delovne temperature, pri delih iz titanovih zlitin, lahko imajo natezne zaostale napetosti, ki jih povzroči ta temperatura, za posledico znatno nižjo utrujenostno trdnost zaradi poškodb površine.

Reducing the thermal load on the ground part significantly influences their quality, represented by residual stresses, Fig. 6 and Fig. 7.

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 likely with lower values of partition ratio (smaller proportion of the energy entering the workpiece). And so CBN and diamond grinding of the VT 9 titanium alloy with cutting fluid enables us 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 titanium alloys, the tensile residual stresses induced at this temperature can result in an appreciably lower fatigue strength due to the surface damage.

Zaradi tega se dandanes nagibamo k temu, da se vključi dodaten postopek mehanskega utrjevanja brušenih površin pri vseh delih v letalski in vesoljski industriji.

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For these reasons there is a current tendency to include an additional operation of mechanically hardening the ground surfaces of all the parts made for the aerospace and space industries.

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3 LITERATURA
3 REFERENCES

[1] Zlatin, N., M. Field (1973) Procedures and precautions in machining titanium alloys, *Titanium Science and Technology*, 1,489-504.

[2] Kahles, J.F., M. Field, E. Eylon, F.H. Froes (1985) Machining of titanium alloys, *Journal of Metals*, IV, 27 – 35.

[3] Rowe, W.B., S.C. Black, B. Mills, H.S. Qi, M.N. Morgan (1995) Experimental investigation of heat transfer in grinding, *CIRP* 44/1, 329-332.

[4] Kato, T., H. Fujii (1999) Energy partition in conventional surface grinding, *Journal of Manufacturing Science and Engineering,* 121, 393-398.

[5] Jeager, J.C. (1942) Moving source of heat and the temperature at sliding contact, *Proc. of the Royal Society of New South Wales,* 76, 203-224.

[6] Peklenik, J. (1957) Ermittlung von geometrischen and physikalischen Kenngrossen für die Grundlagenforschung des Schleifens, PhD. Thesis, Aachen.

[7] Gu, D.Y., J.G. Wager (1988) New evidence on the contact zone in grinding, *CIRP* 37/1/, 335-338.

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

[9] Vasilko, K., G. Bokučava (1988) Brúsenie kovových materiálov, *ALFA* Bratislava.

[10] Darecký, J., S. Novák (1998) Silové a tepelné zaťaženie nástroja pri obrábaní Ni-zliatiny EP 742 VD. *Materiálové inžinierstvo* 12, ŽU Žilina.

[11] Bráneský L'., J. Zajac (1997) Rezné kvapaliny vo výrobe ložísk a ostatných strojárenských technológiách, *Strojárenská technológia a valivé ložiská* 97, Žilina, 46.

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