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Karibek Sherov
S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan

Saule Ainabekova
Karaganda Industrial University, Faculty of metallurgy and mechanical engineering, Temirtau, Kazakhstan

Issa Kuanov
S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan

Balgali Myrzakhme
S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan

Yeldos Bekzhanov
S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan

Riza Gabdyssalik
D. Serikbayev East Kazakhstan University, School of Mechanical Engineering, Ust-Kamenogorsk, Kazakhstan

Assylkhan Mazdubay
Toraigyrov University, Faculty of Engineering, Pavlodar, Kazakhstan

Aman Kamarov
Toraigyrov University, Faculty of Engineering, Pavlodar, Kazakhstan

Aibek Sherov
S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan

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RESEARCH OF TEMPERATURE DISTRIBUTION IN THE PROCESS OF THERMO-FRICTIONAL CUTTING OF TITANIUM ALLOY TI-5553

Karibek Sherov[1,], Saule Ainabekova[2], Issa Kuanov[1], Balgali Myrzakhmet[1], Yeldos Bekzhanov[1], Riza Gabdyssalik[3], Assylkhan Mazdubay[4], Aman Kamarov[4], Aibek Sherov[1]*

[1]S. Seifullin Kazakh Agro Technical University, Faculty of Technical, Nur-Sultan, Kazakhstan
[2]Karaganda Industrial University, Faculty of metallurgy and mechanical engineering, Temirtau, Kazakhstan
[3]D. Serikbayev East Kazakhstan University, School of Mechanical Engineering, Ust-Kamenogorsk, Kazakhstan
[4]Toraigyrov University, Faculty of Engineering, Pavlodar, Kazakhstan

This article presents the results of studying the temperature distribution in the process of thermo-frictional cutting of titanium alloy Ti-5553. The process was simulated using the Machining module of the DEFORM 3D software package based on the finite element method. It was found that when cutting off the titanium alloy Ti-5553, depending on the geometry of the circular saw, the temperature in the "disk-workpiece" contact zone reached T = 800 ÷ 1130 °C, and its propagation into the depth of the workpiece was 0.66 ÷ 0.96 mm. The optimal geometry of a circular saw for cutting off titanium alloy Ti-5553: L1 = 18 mm, L2 = 14 mm, в = 2 mm.
The research was carried out within the framework of the grant № AP09562459.

Key words: thermal cutting, pulse cooling, temperature, heating zone, cooling zone, circular saw

INTRODUCTION

Blank production is one of the key industries in the mechanical engineering industry [1]. The quality and efficiency of technological operations in this production directly affects the indicators of quality and efficiency of the technological process of manufacturing parts. In the conditions of domestic mechanical engineering enterprises, such a technological operation can be called a cutting operation, which is performed on drive hacksaws, on saws (circular, band, friction, etc.) and rarely on lathes (with one or two cutting tools) and on milling machines slotted cutters. Bar stocks are most exposed to parting off. The quality of the cutting operation is influenced by the physical and mechanical properties of the workpiece material. Particularly difficult to part off is materials with high hardness and toughness, which will lead to rapid premature wear and clogging of the tool teeth. These are the materials based on tungsten, nickel, molybdenum, complex alloyed steels, and titanium alloys. Titanium alloys have gained considerable interest due to their wide range of applications in the aerospace, automotive, chemical and medical industries due to their superior properties such as high hot hardness, good strength-to-weight ratio, and high corrosion resistance. And by adding various alloying elements to titanium, it is possible to obtain alloys characterized by higher operational and technological properties [1]. The advantages of titanium and most of its alloys over other known structural materials are associated with its high mechanical properties in a wide temperature range, low density, excellent corrosion resistance to many aggressive media, low temperature, conductivity, non-magnetic, machinability during processing and others, which are qualities, which make it a very attractive material. In this work, the process of thermo-frictional cutting of titanium alloy Ti–5Al–5Mo–5V–3Cr–0.5Fe, is investigated, which patented as Ti-5553. The alloy is a newly developed modification of the Russian titanium alloy VT-22, close to beta, which can be used for aerospace components with thick sections due to its high strength, which reaches 1250 MPa at room temperature for certain microstructures, as well as due to its ability to deep hardening [2],[3],[4].

Ti-5553 alloy has the characteristics of titanium α + β and type β. The tensile strength after annealing can reach 1080 MPa [5]. After heat treatment, the tensile strength can exceed 1500 MPa [6]. Compared to Ti-6Al-4B alloy, the alloy has advantages in hardness, high strength and fracture [7]. Table 1 and 2 show the chemical composition and mechanical properties of the Ti-5553 alloy.

Table 1: Chemical composition of Ti-5553 alloy

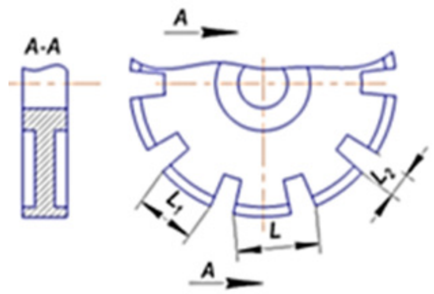
Element	Composition in %	Element	Composition in %
Carbon	0.009	Silicon	0.05
Iron	0.31	Chromium	2.77
Molybdenum	4.71	Oxygen	0.1282
Aluminum	5.12	Nitrogen	0.0055
Vanadium	4.72	Hydrogen	0.0038

*k.sherov@kazatu.kz

Table 2: Mechanical properties of Ti-5553 alloy

Condition	Designation	Composition in %				Strength limit, N/mm^2	Specific force of cutting, MPa	Hardness HB
		Al	Mo	V	Cr			
β-alloy	Ti-5553	5	5	5	3	1160	2400	275-400

Titanium has twice the ductility of steel, making it an ideal choice for applications requiring flexible materials that won't crack or break. In addition, titanium alloys resist corrosion and oxidation better than stainless steels [8],[9],[10]. The following thermo-physical properties of titanium Ti, depending on temperature, in the range from 100 to 2000 K, are given in [11]: titanium density, heat capacity, thermal diffusivity, thermal conductivity of titanium, resistivity, Lorentz function, thermal expansion coefficient. The density of titanium at room temperature is 4500 kg/m3. When heated, titanium expands and its density decreases. The density of liquid titanium at a temperature of about 1700°C is 4120 kg/m^3. The heat capacity of titanium at a temperature of 27°C is 530.8 J/(kg deg) and increases with increasing temperature. The melting point of the Ti-5553 alloy (in degrees) is 1630 ± 5°C. The thermal diffusivity at a temperature of 27°C is about 9.3 106 m2/s. At a temperature close to 883°C, it decreases to 6.9 and increases again. The thermal conductivity of titanium is not high; its value is comparable to the thermal conductivity of stainless steel. The thermal conductivity of titanium at room temperature is on average 16W/ (m deg). As it heats up, the thermal conductivity of titanium increases. When heated at T= 20÷700 °C, the thermal conductivity of titanium fluctuates in the range λ=15.5÷19.4W/m. Alloy Ti-5553 has high strength and fatigue properties at high temperatures and difficulties can be observed during machining. Due to its low thermal properties and high mechanical properties, this alloy is considered difficult to machine [12]. Titanium can be machined like stainless steel. This means that machining titanium is 4-5 times more difficult than conventional steel, but this is still not an insoluble problem. The main problems in titanium processing are its high tendency to sticking and galling, low thermal conductivity, as well as the fact that almost all metals dissolve in titanium, resulting in it being an alloy of titanium and a solid cutting tool material. This processing leads to rapid tool wear. Coolants are used to reduce adhesion and shuffling, as well as to remove a large amount of heat generated during cutting [13]. Also, the low machinability of titanium is associated with a high coefficient of friction, which increases the temperature in the cutting zone. In addition, titanium alloys have an almost two times lower modulus of elasticity, which reduces the rigidity of parts and contributes to the occurrence of vibrations, especially under severe processing conditions. The high reactivity of titanium is the cause of increased chemical wear of the tool [14]. It can be concluded that productive titanium processing requires the use of a special processing method and tool design optimized for these conditions [15]. One of such methods is a thermo-frictional cutting with pulse cooling and the design of the circular saw [16]. Figure 1 shows a sketch and photos of a special circular saw

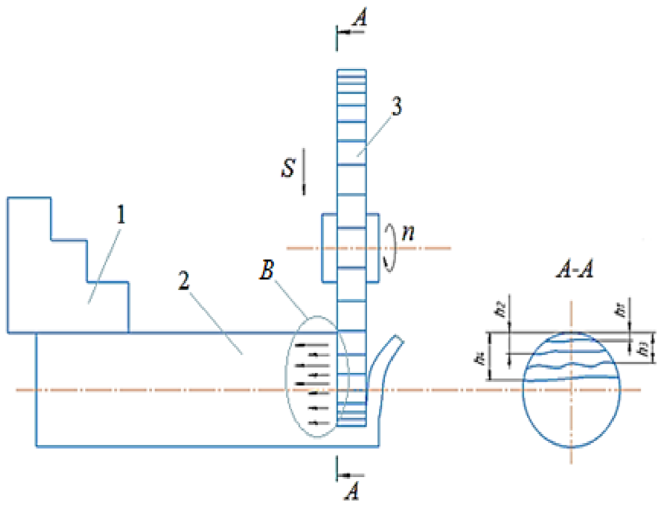


(a)

(b)

Figure 1: Sketch and photos of a special circular saw (a - sketch of a circular saw; b - photos of circular saws; L - tooth pitch; L_1 - heating zone; L_2 - cooling zone)

A special device based on a lathe was developed to implement the method of thermo-frictional cutting with pulsed cooling [17]. Figure 2 shows a diagram of the thermo-frictional cutting process with pulsed cooling. Currently, studies have been carried out to determine the distance of the temperature distribution deep into the workpiece from the “disk-workpiece” contact (look at Fig. 2,b), depending on the cutting conditions and tool geometry. The values of the maximum distance h4, the thickness of the contact layer and the maximum temperature in the "disk-workpiece" contact during the thermo-frictional cut with pulsed cooling St.08. The temperature distribution deep into the workpiece from the end surface of the workpiece (look at Fig. 2, a, callout B), as well as the stress-strain state of the machined surface are of scientific and practical interest. In this case, if the cutting operation is final, then high requirements may be imposed on it regarding structural changes inward from the end surface, which can lead to a change in the distribution of hardness in the deformed layer of the surface. Changes in the hardness of the cut surface and layers adjacent to it can occur for two reasons. Either as a result of work



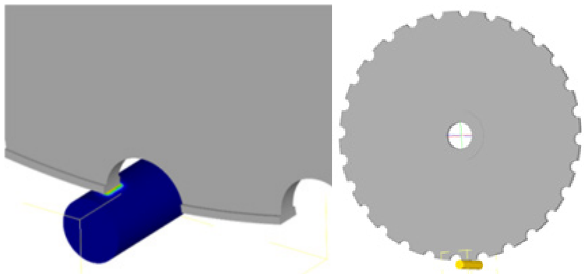
(a) (b)

Figure 2: Process flow diagram of thermo-frictional cutting with pulsed cooling (a – front view; b – incision A-A; S – feed; n – disk rotational speed; h1, h2, h3, h4 – distance of temperature distribution deep into the workpiece from the contact; B – temperature distribution from the end surface; 1 – three-jaw chuck; 2 – work piece; 3 – circular saw)

hardening-work-hardening, or as a result of heat treatment, which can occur due to the heating-cooling cycle. If the cut surface during thermo-frictional parting is hardened to a depth of ≥ 0.5 mm, then this negatively affects the stability of the tool used for processing this surface in the subsequent operation. The design of the circular saw developed by the authors of [16] made it possible to achieve an increase in the cooling efficiency, a decrease in the frequency of heating-cooling cycles i <100*103, the rotational speed of a circular saw to 2000 r/m with a diameter of D = 285 mm. These advantages contribute to the wider application of the method of thermo-frictional parting with pulsed cooling, in particular for the processing of high-strength and high-alloy steels, as well as refractory and titanium alloys, which are difficult to part-off with traditional methods

RESEARCH METHODS

We choose the DEFORM 2/3D software package to study the temperature distribution during a thermo-frictional cut with pulsed cooling of the titanium alloy Ti-5553 [18]. We simulate the process using the Machining module of the Deform 3D software package based on the finite element method [19]. To simulate the process of thermo-frictional cutting with disks of various configurations, the following data were used: model disks Ø285mm with alternating teeth and notches (which is 28 teeth), the so-called heating zones L1 = 18.26 mm and cooling zones L2 = 14.6 mm, respectively pitch L = 32mm, according to the recommendations [20]. Material of the workpiece model titanium alloy Ti-5553 - selected from the program library. Cutting modes: disk rotation speed - nд = 2000, 3000 r/m, feed S = 120 mm/min. The simulation uses a tetrahedral finite element mesh, which is automatically rearranged when distorted [21]. The initial temperature of the workpiece, tool and environment is 20°C. The coefficient of thermal conductivity between the workpiece and the disc is 30W/(m C), between the parts and air - 0.002 W/(m C) [22]. In the boundary conditions of the model, the workpiece is rigidly fixed, the disk moves only along the cutting axis (look at Fig. 2). When the saw is in operation, it is cooled by supplying a jet of water-based coolant. Figure 3 shows a fragment of a cut with a circular saw and a view of a model of a disk and a workpiece with a distributed finite element mesh.



(a) (b)

Figure 3: Fragment of a cut with a circular saw and a view of a model of a disk and a workpiece with a distributed mesh of finite elements (a - a fragment of a cut off with a circular saw; b – a view of a disk with workpiece)

The strength characteristics for the workpiece are specified using the Johnson-Cook model [23]:

$$\sigma_s = (A + B\varepsilon^n)\left(1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right)\left(1 - \left(\frac{T - T_0}{T_{пл} - T_0}\right)\right)^m$$

where ε - the accumulated deformation of the workpiece material;

$\varepsilon^{\cdot}$ - average deformation rate of the workpiece material in the cutting zone;

T - average temperature of workpiece material in the cutting zone;

Tmelting, T_0 - melting temperature of the workpiece material and its temperature corresponding to $(\varepsilon_0)^{\cdot}$ (usually T_0 = 20°C);

$(\varepsilon_o)^{\cdot}$ - deformation rate of the workpiece material at temperature T_0;

A, B, п, C, т - coefficients obtained as a result of statistical processing of experimental data on the strength characteristics of the workpiece material.

The Cockcroft – Latham model was used as a fracture criterion for both steels [24],[25].

$$\int_0^{\varepsilon_i} \frac{\sigma_1}{\sigma_i} d\varepsilon_i < c_{lim},$$

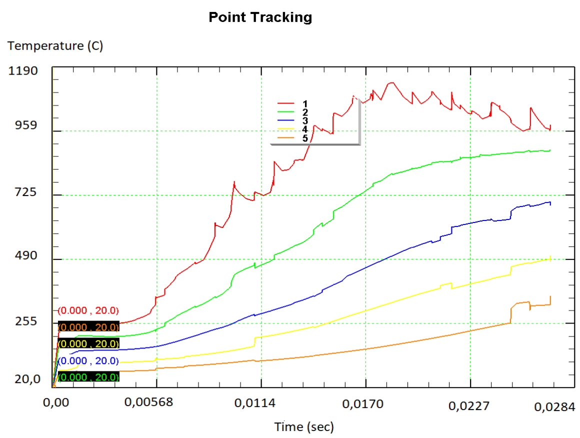
where σ1 – main normal stress; σi – stress intensity; εi – deformation intensity; clim – limit value of the Cockcroft-Latham index. The material of the circular saw during modeling is AISI 4140 (analogue of steel 40XM). DEFORM has a built-in base for this steel with dependencies: elastic modulus - temperature, yield point - deformation for various strain rates and temperatures, and values of heat capacity, thermal conductivity [23]. Thermal conductivity of AISI 4140 steel λ≈42.6 W/(m°C). Johnson-Cook model parameters for AISI 4140 steel: A = 598 MPa; B = 768 MPa; C = 0.0137; n = 0.2092; m = 0.807; (εo) ̇=0.001c-1. Titanium alloy was used as a workpiece material during modeling, the parameters of the Johnson-Cook model of which are presented in Table 3.

Table 3 - Johnson-Cook model parameters for titanium alloy Ti-5553

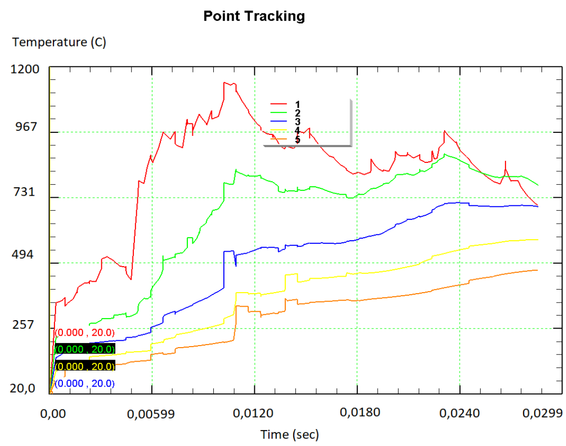
A	B	n	C	m
1175	728	0,26	0,09	0,72

EXPERIMENTAL STUDY AND DISCUSSION OF RESULTS

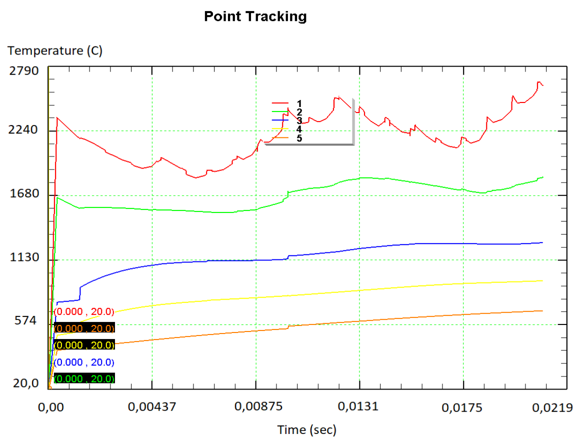
Let us consider the temperature distribution during modeling using the DEFORM-3D program of the process of thermo-frictional cutting with disks with different geometries - with a heating zone L1 = 26, 18 mm and a cooling zone L2 = 6, 14 mm, respectively. The workpiece section was marked to determine the temperature change in the contact layer to determine the temperature in the surface layer of the workpiece. For these points in the DEFORM 3D program, graphs of the dependence of the temperature change on the time of the segment are plotted, which is one disk revolution. As a result of modeling, the temperature distribution into the depth of the workpiece in the "tool-workpiece" contact zone was obtained. Figure 4 shows graphs of temperature distribution depending on the time of the segment with the marking of the contact layer deep into the workpiece at different sizes L1 и L2. The results of the analysis of the graphs of the dependence of the temperature change on the time of the segments per revolution of the disk for different sizes of the geometry of the circular saw are included into table 4.



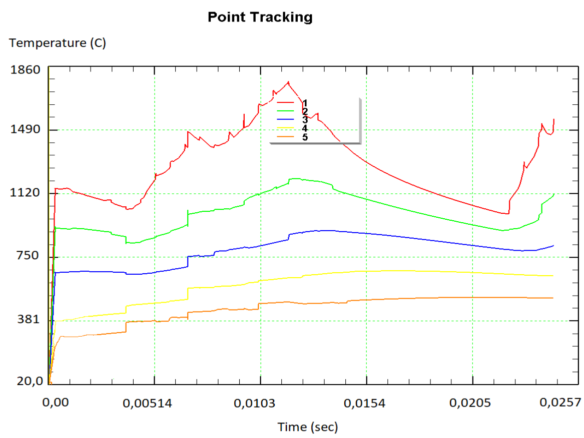
(a)



(b)



(c)



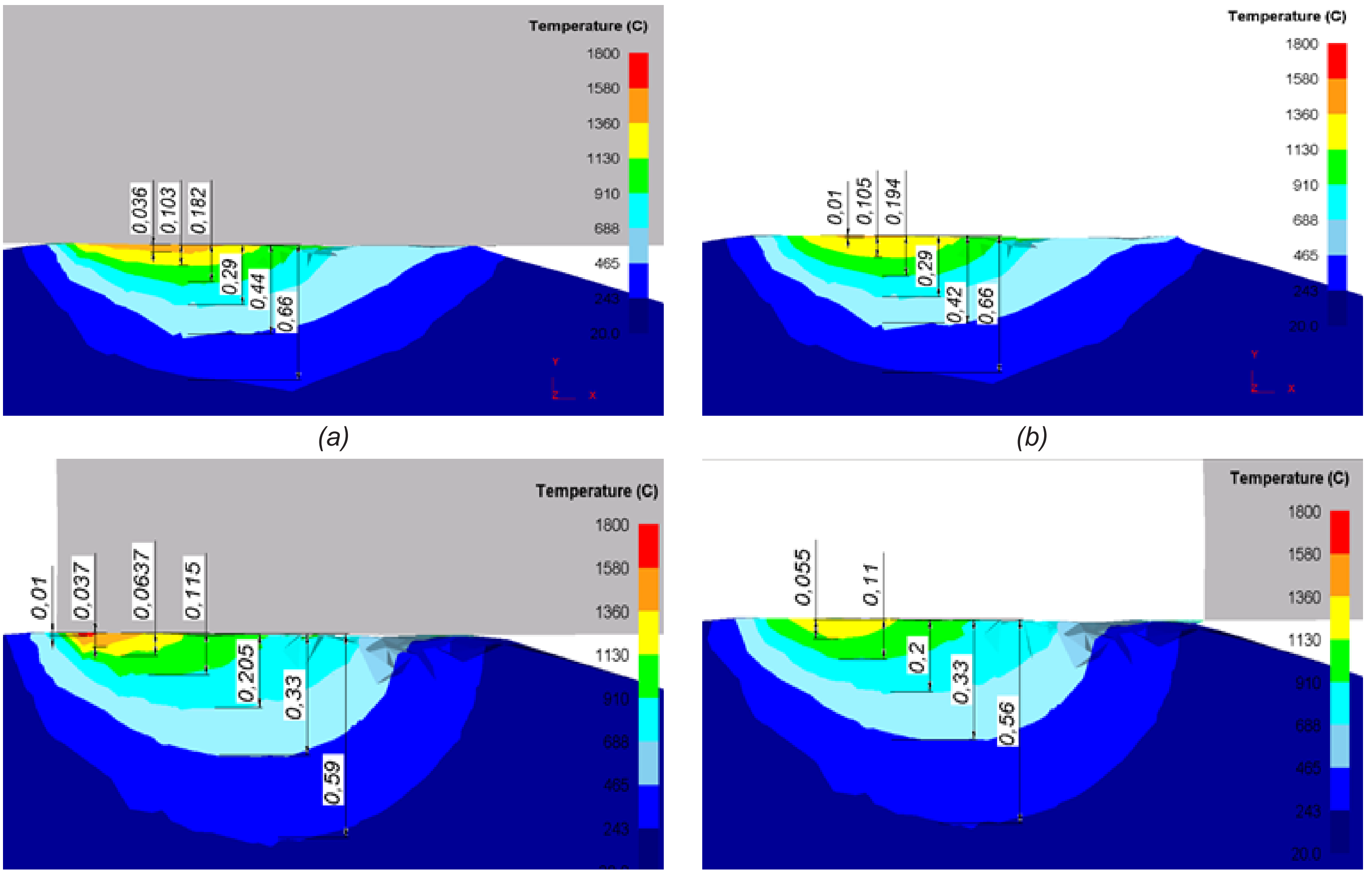
(d)

Figure 4: Graphs of the temperature distribution depending on the time of the segment with the marking of the contact layer deep into the workpiece for different sizes L1 u L2 (a,c - $n_д$ =2000 r/min; b,d – $n_д$ =3000 r/min; a, b - L_1=18 mm, L_2 =14 mm; c,d - L_1= 26 mm, L_2 = 6 mm; S = 120 mm/min)

Table4: The results of the analysis of the graphs of the dependence of the temperature change on the time of the segments per revolution of the disk for different sizes of the geometry of the circular saw

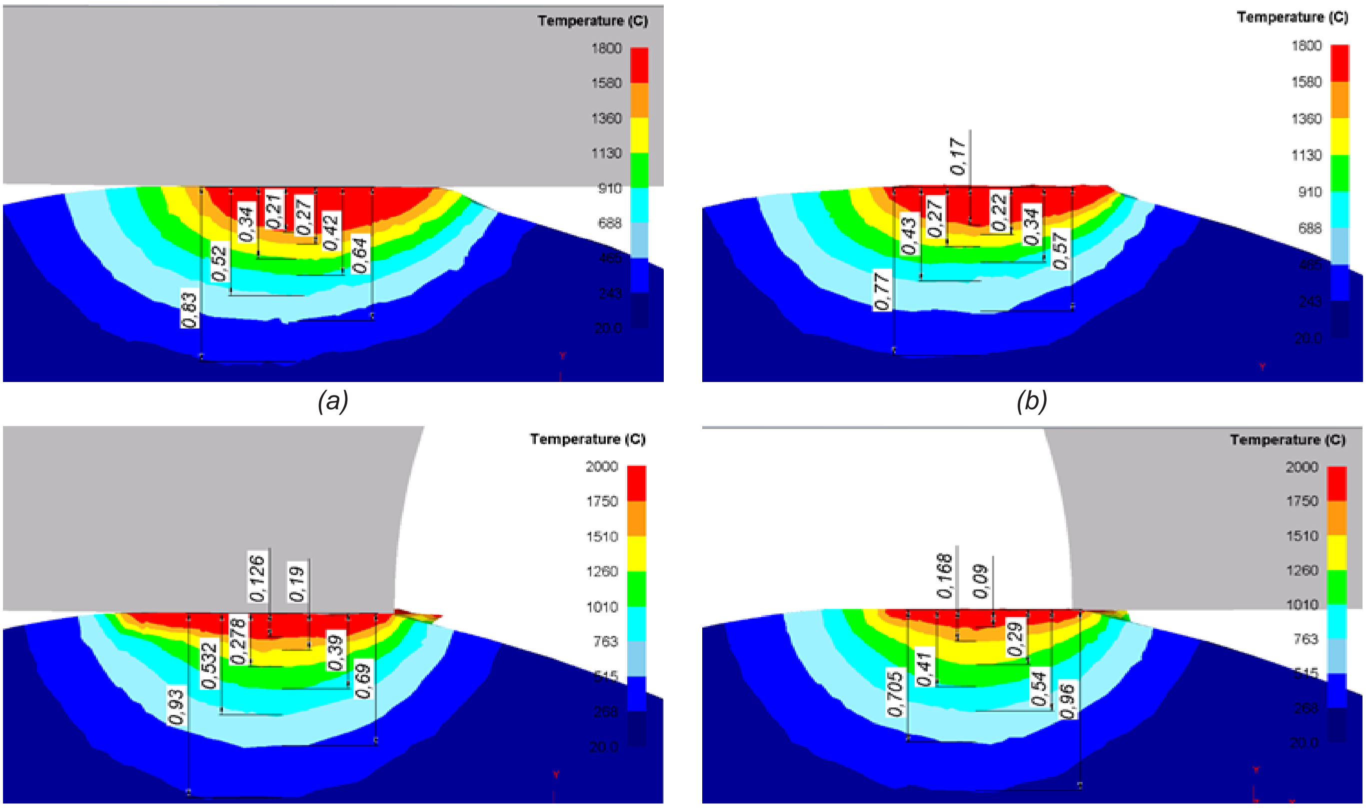
The geometry of the circular saw		The rotation speed of the circular saw, n_∂, r/min	Time to establish the processing process, sec	Achieved temperature, T,°C
L_1, mm	L_2, mm			
18	14	2000	0,0114	800
		3000	0,0059	900
26	6	2000	0,0011	1130
		3000	0,0009	1120

The results showed (look at Fig. 4 and Table 4) that the value of the time to establish the process of thermo-frictional cutting with impulse cooling at different cutting conditions and geometries of the circular saw are in the range 0.0009 ÷ 0.0114 sec. In this case, the values of the achieved temperature fluctuate within the limits of T = 800 ÷ 1130 °C. Figure 5 shows the models of temperature change during one revolution of the disk in the heating and cooling zones, with L1 = 18 mm; L2 = 14 mm. Figure 6 shows models of temperature change in one revolution of the disk in the heating and cooling zones, with L1=26 mm; L2 =6 mm. The workpiece section was marked to determine the temperature in the surface layer of the workpiece. These points were used to plot the dependences of the temperature change in each section on the time of the segment. Let us analyze the change in temperature per one rotation of the disk in the process of thermo-frictional cutting with pulsed cooling of the titanium alloy Ti-5553 at different sizes of the heating zone L1 and the cooling zone L2, as well as at different rotational speeds of the circular saw nd. From Figures 5 and 6, as well as from Table 4, it can be seen that with a disk with a heating and cooling zone size of 26 and 6 mm, respectively, the temperature in the "tool-workpiece" contact



(d)

Figure 5: Models of temperature change in one revolution of the disk in the heating and cooling zones, with L_1=18 mm; L_2 =14 mm (a,b - n_∂ =2000 r/min; c,d – n_∂ =3000 r/min; S= 120 mm/min; в = 2 mm; a,c – heating zone models L_1=18 mm; b,d – cooling zone models L_2 =14 mm)



(c) (d)

Figure 6: Models of temperature change in one revolution of the disk in the heating and cooling zones, with L_1=26 mm; L_2= 6 mm (a,b - $n_д$ =2000 r/min; c,d – $n_д$ =3000 r/min; S= 120 mm/min; в = 2 мм; a,c – models of heating zone L_1=26 mm; b,d – models of cooling zone L_2 =6 mm)

zone is higher than with a disk with a heating and cooling zone size of 18 and 14 mm.

The results of the analysis of the temperature change for one revolution of the disk in the heating and cooling zones at L1 = 18 mm; L2 = 14 mm (look at Fig. 5) showed that the maximum distance of temperature distribution into the depth of the workpiece is 0.66 mm. At the same time, the temperature fluctuates in the range T = 200 ÷ 1800oC. An increase in the rotational speed of the circular saw leads to an increase in the contact temperature and at the same time the distance of temperature propagation into the depth of the workpiece. With L1 = 24 mm; L2 = 6 mm (look at Fig. 6) the maximum distance of temperature distribution deep into the workpiece is 0.96 mm. In this case, the temperature in the contact "tool-workpiece" reaches up to T = 2000 oC. The results showed that at smaller sizes of the heating zone L1 = 18 mm, the conditions necessary for the cutting process are provided and the temperature spreads to a smaller depth. This can be explained by the low thermal conductivity of the titanium alloy, which prevents the propagation of heat into the depth of the workpiece and contributes to the sharp localization of heat in the tool-workpiece contact zone

CONCLUSIONS

As a result of studying the temperature distribution in the process of thermo-frictional cutting of titanium alloy Ti-5553 using the DEFORM 3D software package, it was found that:

- the low thermal conductivity of the titanium alloy Ti-5553 favorably affects the intensity of the temperature concentration directly in the "disk-workpiece" contact and, at the same time, reduces the time to establish the cutting process;
- the value of the time to establish the process of thermo-frictional cutting of titanium alloy Ti-5553 at different cutting conditions and geometry of the circular saw are in the range of 0.0009 ÷ 0.0114 sec. In this case, the values of the reached contact temperature fluctuate within the limits of T = 800 ÷ 1130 °C.
- the distance of temperature distribution in the process of processing deep into the workpiece, at various cutting conditions and dimensions of the geometry of the circular saw, is in the range of 0.66÷0.96 mm. In this case, the temperature fluctuates in the range T = 200÷1800 °C.
- taking into account the mechanical properties of titanium alloys, in particular Ti-5553, the optimal geometries of the circular saw were selected: L1 = 18 mm, L2 = 14 mm, b = 2 mm.

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