An Analytical and Experimental Study of the Grinding Process of Thermal Barrier Coatings With Highly Porous Wheels of Cubic Boron Nitride

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Abstract.
To protect heat-resistant alloys from high-temperature oxidation, thermal barrier coatings are widely used. Practical application, in accordance with the requirements arising during operation, found a coating of ZrO_2. Zirconia based ceramics are highly durable and crack resistant. In the grinding process, high contact temperatures arise, the values of which are comparable to operating temperatures or slightly higher than these temperatures.
The task in the design of the grinding process is primarily to control the thermal treatment mode in order to maintain it within such limits when the residual stresses have values that do not pose a danger to the durability of the sprayed layer.
In addition, if the contact temperature of grinding reaches 1200ºC, then the sintering of the sprayed layer begins, which leads to the loss of thermal barrier properties.
When grinding with highly porous CBN wheels with a structure 26 and 40, the unit cutting forces are 15–20% higher, and the total cutting forces are 7–10% lower. When grinding with highly porous wheels, contact temperatures are 10-15% lower.
The residual stresses arising under the action of contact temperatures on the surface during grinding of pure zirconium oxide and stabilized with yttrium oxide reach values of the order of 60 MPa, however, these values are much lower than the tensile strength of the thermal barrier layer and do not lead to cracks.
When grinding with highly porous wheels, an increase in roughness by 1 category can be expected.
When grinding with highly porous CBN wheels grinding modes can be increased by 20-25%.

Keywords: highly porous wheels, unit force, total force, unit temperature, contact temperature, temporary stresses, residual stresses.

1 Introduction

To protect heat-resistant alloys from high-temperature oxidation, thermal barrier coatings are widely used. Three basic requirements are imposed on thermal barrier coatings: low thermal diffusivity, resistance to cracking at high temperatures, and increased service life. Most fully meets these requirements thermal barrier coating of ZrO_2. Zirconia-based ceramics are highly durable and crack resistant.

In the process of grinding thermal barrier coatings, high contact temperatures arise, the values of which are comparable to operating temperatures or slightly higher than these temperatures.

At present, CBN grinding with highly porous «AEROBOR» grinding wheels has become quite widespread.

When grinding with such wheels, it should be borne in mind that initially the content of CBN grains in a unit volume of the CBN layer is much lower than that of circles of the N6 structure, which corresponds to ordinary CBN wheels.

2 Literature Review

It should be noted that in the modern literature there is no clear data on the thermodynamics of this grinding. It is noted that the contact temperature of grinding is usually lower than when grinding with ordinary wheels. There is little information on cutting forces during grinding, and they are contradictory.

So in [1] new CBN wheels are considered and some questions of their application are considered. However, the issues of grinding thermal barrier coatings or tiles of ZrO_2 are not considered. The issues of determining contact grinding temperatures are also not considered.

In [2], the grinding process with porous wheels from CBN is considered in detail. However, grinding ceramics is not considered and data on contact grinding temperatures are not given; there is no data on the values of unit cutting forces.

The work [3] deals with the grinding of highly plastic alloys with CBN wheels from CBN. However, this work does not address the issues of grinding ceramics.

In [4], grinding by highly porous circles of aluminum alloys is considered. Ceramic grinding not investigated

The work [5] deals with grinding without cooling various alloys. However, the issue of grinding ceramics ZrO_2 is not considered. In addition, the authors measure not the grinding temperature, but the average temperature of the part before and after grinding, which gives little information and the process.

In [6], grinding issues with highly porous CBN wheels are considered; however, ceramic grinding and contact grinding temperature are not considered.

In [7], the grinding process is considered by highly porous CBN wheels from the point of view of minimizing the number of edits, and high porosity is considered as a means of delivering coolant to the cutting zone. Ceramic grinding issues are not considered.

The work [8] considers the grinding of hard-to-work materials - titanium and nickel alloys, as well as the determination of the most advantageous porosity of a wheel from the point of view of preserving grain holding forces by a binder. It was shown that porosity of 30% showed the best results. The issue of grinding ceramics is not considered.

In [9], the process of profile gear grinding by highly porous abrasive wheels is studied. Recorded data on reducing cutting power and improving the accuracy of polished gears. However, in this work only abrasive wheels are considered and there is no information about grinding ceramics.

It can be concluded that despite the large number of works carried out to study the grinding process with CBN highly porous wheels, many questions have not been fully clarified. So, the characteristics that are directly related to the working conditions of the grain of the highly porous CBN circle - the cutting force of the grain and the temperature of the cutting of grain - have not been clarified. Little data is available on the total grinding forces, contact grinding temperatures, and thermal residual stresses in the surface layer. The issue of grinding ceramics is almost not considered.

It can be argued that at present there is no database on the grinding regimes of high-porous CBN wheels for ceramic thermal barrier coatings that would ensure the properties of the thermal barrier layer after processing are unchanged.

Based on this, in the present work, mathematical modeling of the grinding process with CBN wheels was carried out with a point experimental verification of the results.

The developed mathematical model [10] adequately reflects the performance of the grinding process with CBN wheels and can show the main trends in the cutting process.

3 Literature Review

The research was aimed primarily at studying of the grinding forces, grinding temperatures and establishing patterns of heat field propagation in the thermal barrier layer. The main attention was paid to obtaining the dependences of the change in the temperature field on the largest possible number of factors of the grinding process.

So varied processing modes, grain of wheels and the effect of the supplied coolant.

The study of power dependencies when grinding with CBN wheels AEROBOR Features of grinding with highly porous wheels is that the ratio per unit volume of grains and pores is significantly increased in favor of pores. This means that the number of active cutting grains per unit surface of the CBN circle is significantly reduced. From this it follows that the allowance is removed with a smaller number of grains in comparison with the circles of porosity 6. Therefore, each grain removes larger chip, and higher unit cutting forces can be expected during processing. (Table 1-2. Fig. 1).

The total cutting forces that are formed by summing the unit forces from the grains in the contact patch of the circle with the part, i.e. a smaller number of grains developing a greater unit force is added up. Theoretically, the total force can be either greater or less than the cutting forces when grinding with ordinary wheels. Our mathematical modeling shows that the total forces are somewhat reduced.

It should be noted that the relatively large unit forces Py cause large values of temporary stresses. The magnitude of these stresses in some cases is higher than the compressive strength of the sprayed layer. This may cause cracking. These cracks do not develop, since the sprayed layer is porous and a crack can develop for the time being. Examination of the grinded surface does not show the presence of cracks from temporary stresses.

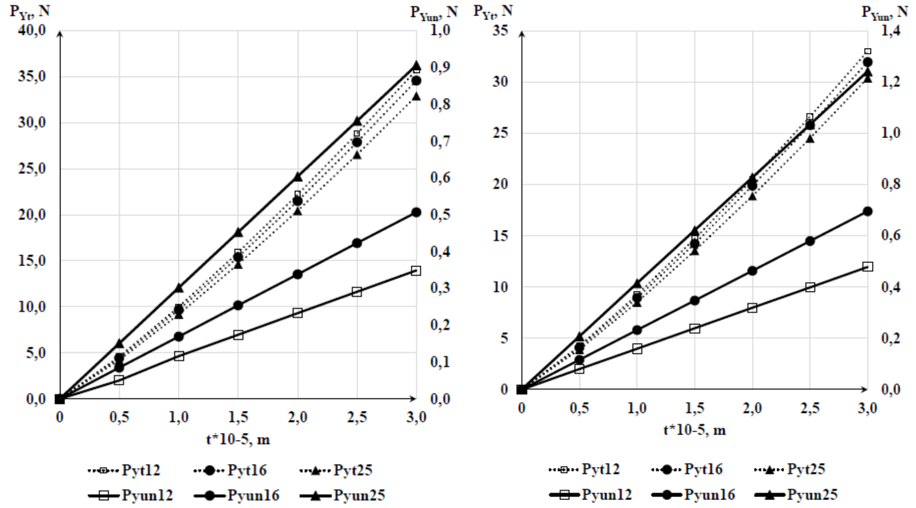
Table 1. Values of unit P_{Zun} and total P_{Zt} forces when grinding with wheels LO250/160C10 100% (Nz25) structure N6 and AEROBOR (Nz25) N26 и N40

$t*10^{-5}$ m	P_{Zun} H			P_{Zt} H		
	The structure of the CBN wheel and the AEROBOR wheel; Nst					
	6	26	40	6	26	40
0,5	0,31	0,37	0,39	1,50	1,42	1,40
1,0	0,52	0,63	0,66	3,12	2,94	2,89
1,5	0,70	0,85	0,89	4,80	4,55	4,47
2,0	0,88	1,05	1,11	6,60	6,24	6,13
2,5	1,04	1,24	1,31	8,50	8,00	7,85
3,0	1,19	1,42	1,50	10,40	9,81	9,63

Table 2. Values of unit P_{Yun} and total P_{Yt} forces when grinding with wheels LO250/160C10 100% (Nz25) structure N6 and AEROBOR (Nz25) N26 и N40

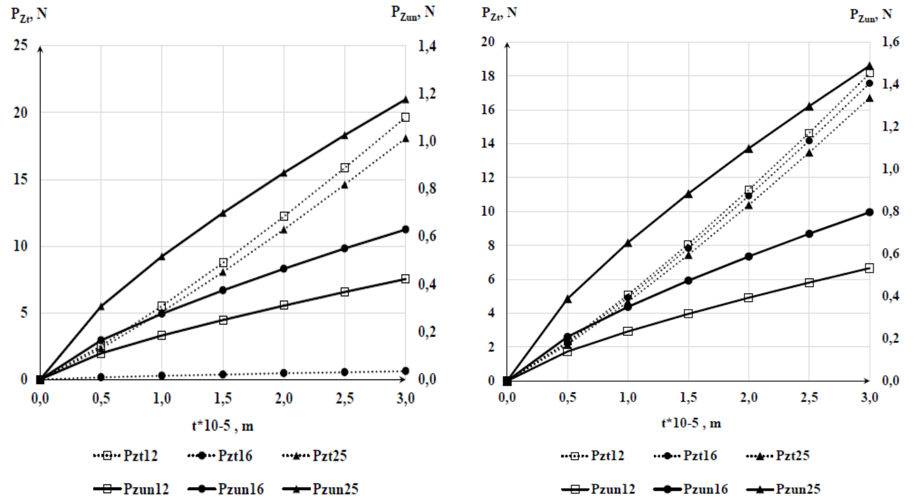
$t*10^{-5}$ m	P_{Yun}, H			P_{Yt}, H		
	The structure of the CBN wheel and the AEROBOR wheel; Nst					
	6	26	40	6	26	40
0,5	0,15	0,20	0,21	2,75	2,59	2,54
1,0	0,31	0,39	0,42	5,68	5,34	5,25
1,5	0,46	0,59	0,63	8,79	8,27	8,13
2,0	0,61	0,78	0,84	12,06	11,35	11,15
2,5	0,76	0,97	1,05	15,45	14,54	14,28
3,0	0,15	1,17	1,26	18,95	17,83	17,52

The total cutting forces P_{Zt} are slightly reduced. This is due to the fact that the number of cutting grains in the contact patch is reduced. Despite the fact that unit forces are slightly higher. However, an increase in unit forces from each grain cannot compensate for a decrease in the number of cutting grains in the contact spot.



a) b)

Fig. 1: The values of the unit and total cutting forces Py during grinding with CBN circles of structure No. 6 - a) and structure No. 40 – b). Modes Vw = 30 m/s; Vsp = 0.166 m/s; S = 0.002 m / rev (LO250/160 C10 100% (Nz25))



a) b)

Fig. 2. The values of the unit and total cutting forces Pz during grinding with CBN circles of structure No. 6 - a) and structure No. 40 – b). Modes :Vw = 30 m/s; Vsp = 0.166 m/s; S = 0.002 m / v. .(LO250/160 C10 100% (Nz25))

An increase in unit cutting forces P_{Yed} causes an increase in temporary stresses. So, under the above grinding conditions, temporary stresses for N6 are 6244 MPa, for structure N26 – 6635 MPa and for structure N 40 – 6755 MPa. Thus, temporary stresses increase.

The values of temporary stresses are significantly higher than the compressive strength of ZrO_2. Such stresses should cause cracks in the sanding layer, but, as indicated in [11], cracks do not develop due to the porosity of the sprayed layer.

Table 3. Values of temporary stresses during grinding by wheels LO250/160 C10 100% (Nz25) structure N6 and AEROBOR (Nz25) structure 26 and 40

$t*10^{-5}$ m	$\Sigma_{temp}*10^6$ Па		
	The structure of the CBN wheel and the AEROBOR wheel; Nst		
	6	**26**	40
0,5	1537	1736	1799
1,0	2174	2455	2544
1,5	2662	3007	3116
2,0	3074	3472	3598
2,5	3437	3881	4023
3,0	3765	4252	4407

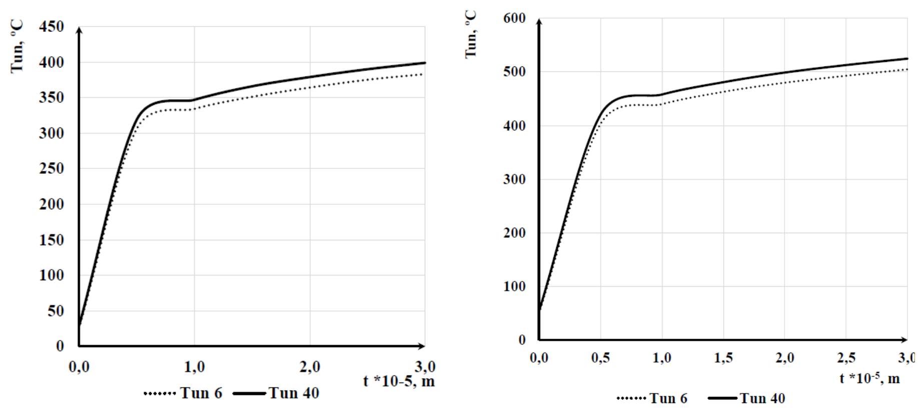
Single grain cutting temperatures

Unit cutting forces are slightly greater when grinding with highly porous circles. This suggests that the cutting temperatures of single grains will be slightly higher compared to the temperatures that occur when grinding with circles of structure No. 6.

Mathematical modeling has confirmed this assumption. The results are shown in table 4 and in the graphs of Fig. 3**.**

Table 4. Comparison of temperatures from single grains during grinding with wheels (LO250/160 C10 100% (Nz25)) of structure 6: and 40

t, m^{-5}	N=12		N=16		N=25	
	Tun 6	Tun 40	Tun 6	Tun 40	Tun 6	Tun 40
0,0	26	29	34	38	50	54
0,5	306	319	341	355	403	420
1,0	334	347	372	387	440	458
1,5	351	366	391	407	463	481
2,0	364	379	406	422	480	499
2,5	375	390	417	434	493	513
3,0	383	399	427	444	505	525



a) b)

Fig. 3. Unit temperatures of grain cutting during grinding by circles. (LO250/160 C10 100% (Nz25)) of structure No 6 and No 40. Modes Vw = 30 m/s; Vsp = 0.166 m/s; S = 0.002 m / v

Analyzing the results, we can conclude that the unit temperature of cutting grain during grinding with highly porous wheels slightly highe.

Contact temperatures and residual stresses

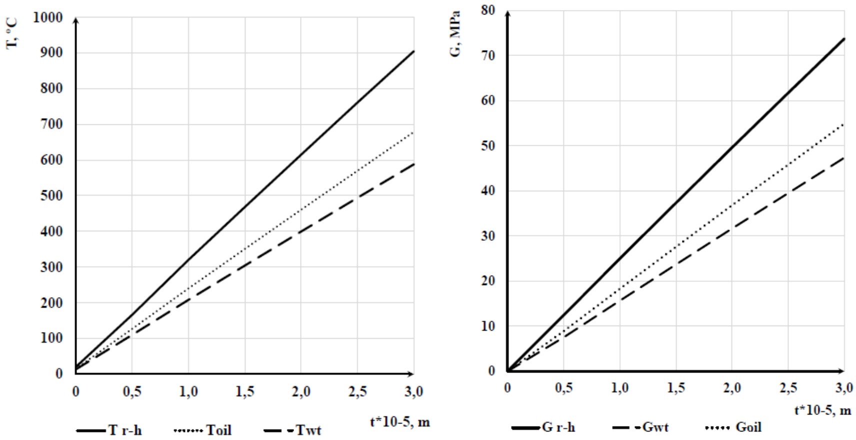
Simulation of the thermal process during grinding with highly porous wheels shows that since the total cutting forces are slightly reduced, the power of the heat source Pz * Vw also decreases, which causes a corresponding decrease in temperature. Fig.4. The thermal process was simulated without taking into account the thermodynamics of cooling the surface with air through the pores of the wheel. The total decrease in temperature can be no more than 5-10%. When considering the thermodynamics of cooling, it should be borne in mind that the cooling effect of an air is about 10 times less than when cooling with water-based coolant, so it is impossible to expect large heat transfer from the surface heated by grinding. As shown by thermodynamic calculations [11], the heat transfer coefficient when blowing the zone of contact of the circle with the part through the pores of the circle is not more than 200 $W/m^2\ {}^0K$. Considering the insignificant area of the contact spot of the circle with the part, the heat transfer from it is insignificant. Approximate calculations show that the temperature decrease can be no more than 8-10%. Consequently, given the decrease in the power of the heat source and the cooling effect of air, we can expect a decrease in the contact temperature by 15-20%. Contact temperature measurements using microthermocouples confirm this assumption.

Residual stresses are formed by contact temperatures. In the case of grinding with highly porous wheels, all the laws governing the formation of residual stresses are the same as when grinding with ordinary wheels. Since the contact temperature is lower, the stresses are also lower than in the case of grinding with ordinary wheels.

In general, grinding with highly porous CBN wheels can increase the limiting processing conditions by 15-20%.

The most effective contact grinding temperature can be reduced by feeding mineral oil or water-based coolant to the contact zone.

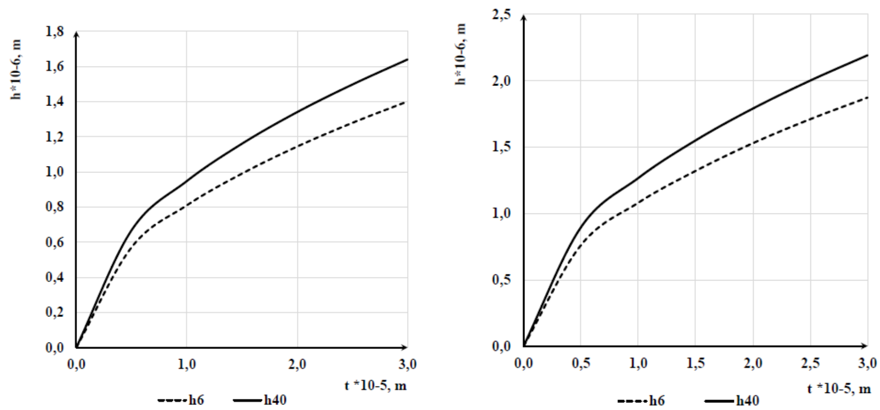
Modeling of such grinding conditions showed that a decrease in temperature can reach up to 35-40%, which naturally makes it possible to significantly tighten grinding modes, in particular, it is possible to switch to high-speed grinding without fear of causing defects on the thermal barrier layer (Fig.4).



a) b)

Figure 4. Contact temperatures (a) and residual stresses (b) when grinding CBN with wheels of structure No. 40 when cooling with air (using a Ranque-Hillsch tube), when cooling with oil and water-based coolant. Modes Vcr = 30 m/s; Vdet = 0.166 m/s; S = 0.002 m/v (LO250/160 C10 100% (Nz25))

It is rather difficult to simulate the roughness value; therefore, the roughness state was estimated indirectly by the magnitude of the grain deepening in the material. The results of the comparative analysis are shown in Fig. 5.



a) b)

Fig. 5. The magnitude of the deepening of grain into material l when grinding CBN with wheels .(LO250/160 100% (Nz25)) of structure No. 6 and structure No. 40. Modes Vw = 30 m/s; Vsp = 0.166 m/s; S = 0.002 m / rev. Grain a) Nz = 12; b) Nz = 25

As can be seen from the above graphs, the magnitude of the deepening of the grain in the material for highly porous circles is 10 - 13% more, so we can expect an increase in roughness by about 1 category.

4 Results

As a result of mathematical modeling of the process of CBN grinding of thermal barrier coatings of ZrO_2 and $ZrO_2 + Y_2O_3$, it was found:

1. The values of the cutting force component Py, depending on the processing conditions, can reach values of the order of 20N. The values of the component of the cutting force Pz, depending on the processing conditions, can reach values of 10H. Cutting forces do not cause temporary stresses that could lead to cracks in the sprayed ZrO2 layer.

When grinding with highly porous CBN 26 and 40 circles, the unit cutting forces are 15–20% higher, and the total cutting forces are 7–10% lower.

When grinding with highly porous circles, contact temperatures are 10-15% lower. Calculations carried out according to the developed mathematical model show that under sufficiently intense grinding conditions with highly porous CNB wheels, the grinding temperature is in the range below 1100^0C. This temperature value excludes sintering of the surface sprayed layer and a decrease in its thermal barrier properties.

2. The temporary stresses during grinding of pure zirconium oxide and stabilized with yttrium oxide by ordinary CBN wheels and highly porous are in the range of 3700-4400 MPa. In some cases, the stress exceeds the compressive strength, however, due to the porosity of the sprayed layer, the crack does not develop in depth.

3. Residual stresses arising under the influence of contact temperatures on the surface during grinding of pure zirconium oxide, stabilized zirconium oxide with yttrium oxide, wheels of ordinary porosity, and highly porous wheels reach significant values of the order of 60 MPa, however, these values are much lower than the tensile strength of the thermal barrier layer and do not lead to cracks, naturally within the framework of the studied processing regimes.

4. When grinding with highly porous wheels, an increase in roughness by 1 category can be expected.

5. When grinding with highly porous CBN wheels, grinding conditions can be increased by 20-25%.

Conclusions

Grinding with highly porous CBN circles of ZrO_2 thermal barrier coatings makes it possible to obtain good results when grinding without cooling, since the surface, although slightly cooled by blowing air through the pores of the circle under fairly intense processing conditions.

Due to the fact that the surface roughness increases somewhat, it is necessary to provide nursing passes when constructing the operation, when unit forces are minimal and the roughness can be reduced.

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