TWO LAYERED COATING – SURFACE ROUGHNESS OF NiAl AND Al_2O_3 + 13% TiO_2 LAYERS

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Formation of a ceramic coating layer (Al_2O_3 + 13% TiO_2) takes place by a gradual deposition (overlapping) of non-uniformly deformed particles irregularly distributed over the NiAl surface layer and then over the ceramic layer surfaces. This results in a layer with a rough surface and containing some microvoids (pores). This generally applies also to other types of metallic and ceramic layers (coatings). Surface roughness of a metallic or ceramic layer depends first of all on the powder granularity. Under the given conditions, the surface roughness is stabilized at values around $Ra = 6$–8 μm (NiAl) or $Ra = 3$–5 μm (Al_2O_3 + 13% TiO_2). The effect of substrate surface roughness on surface roughness of the NiAl layer (and also the effect of metallic layer surface roughness on surface roughness of the ceramic layer) depends on the difference between the surface roughness of substrate surface (NiAl layer) and a stabilized surface roughness of the NiAl layer (Al_2O_3 + 13% TiO_2 layer) as well as on the required layer thickness. The surface roughness of the ceramic layer ($Ra = 3$–5 μm) can be improved by polishing ($Ra = 1$–2 μm) or grinding (in the given conditions $Ra = 0.8$–0.9 μm). A better surface roughness can be achieved by altering the grinding conditions but mainly by the use of a diamond grinding wheel with smaller dimensions of abrasive grain size.

DVOJVRSTVOVÝ POVLAK – DRSNOSŤ POVRCHU VRSTIEV NiAl A Al_2O_3 + 13% TiO_2

Keramická vrstva povlaku (Al_2O_3 + 13% TiO_2) sa tvorí postupne prekrývaním rôzne deformovaných častíc, nerovnomerne rozdelených na povrchu vrstvy NiAl a následne na povrchoch keramickej vrstvy. Výsledkom je vrstva, ktorá má drsný povrch a obsahuje póry. To platí aj pre iné typy kovových a keramických vrstiev. Drsnosť povrchu kovových

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a keramických vrstiev závisí predovšetkým od zrnitosti použitých práškov. V daných podmienkach sa drsnosť povrchu stabilizovala na hodnotách Ra = 6–8 μm (NiAl) a Ra = 3–5 μm (Al_2O_3 + 13% TiO_2). Vplyv drsnosti povrchu substrátu na drsnosť povrchu vrstvy NiAl (a tiež vplyv drsnosti povrchu NiAl na drsnosť povrchu keramickej vrstvy) závisí od rozdielu medzi drsnosťou povrchu substrátu (vrstvy NiAl) a stabilizovanou drsnosťou povrchu vrstvy NiAl (Al_2O_3 + 13% TiO_2), ako aj od požadovanej hrúbky vrstvy NiAl (Al_2O_3 + 13% TiO_2). Drsnosť povrchu keramickej vrstvy (Ra = 3–5 μm) môžeme zlepšiť leštením (Ra = 1–2 μm) alebo brúsením (v daných podmienkach Ra = 0,8–0,9 μm). Menšiu drsnosť povrchu môžeme dosiahnuť zmenou podmienok brúsenia, ale najmä použitím diamantového brúsneho kotúča s menšími rozmermi zŕn.

1. Introduction

Plasma spraying produces coatings with specific properties. These are for example wear resistant coatings, electrically insulating or electrically conductive coatings etc. In practice, we use either as-sprayed coatings, or in the case of special dimension or surface-roughness requirements, mechanical machining is employed.

In plasma spraying, the coating material is supplied to the plasma jet in powder form. The particles are heated in the plasma jet by the energy of flowing gases and are deposited on the substrate surface where a typical layered structure is formed. In the plasma spraying of ceramic coatings on a metallic surface a great number of small pores is formed in the boundary on the ceramic layer side. These voids arise mainly as a result of lateral spreading that occurs when the molten metallic particles impinge on the cooler substrate surface [1]. The voids formed by the extensive lateral spreading of the splats reduce the actual ceramic-metal contact and thus impair the bond efficiency [1]. Substrate surface roughness confines the lateral spreading improving the bonding efficiency. With increasing grain size of the sprayed powders the surface roughness of the as-sprayed coating increases [2], [3], [4]. The coating surface roughness depends also on the power level and the stand-off distance [4].

The final surface roughness of the coating depends on [5]: (i) the surface roughness of the substrate after grit-blasting, (ii) the degree of fusion and flow of the selected powder. According to experimental results [6] surface roughness has an influence on interface strength.

Temperature in the transverse and longitudinal direction of a plasma jet varies considerably [7]. Thus, the thermal conditions of a particle prior to impinging on the substrate depend on its path in plasma jet. In general, the particles prior to impinging on the substrate possess different thermal conditions, kinetic energy, and are deformed to different extent after reaching the substrate. Thus, it follows that the coating contains different types of particles dissipated gradually on the rough substrate surface and then in the coating layer.

The aim of this work was to study surface roughness in formation of the two layered coating: NiAl + (Al_2O_3 + 13% TiO_2), the effect of substrate surface

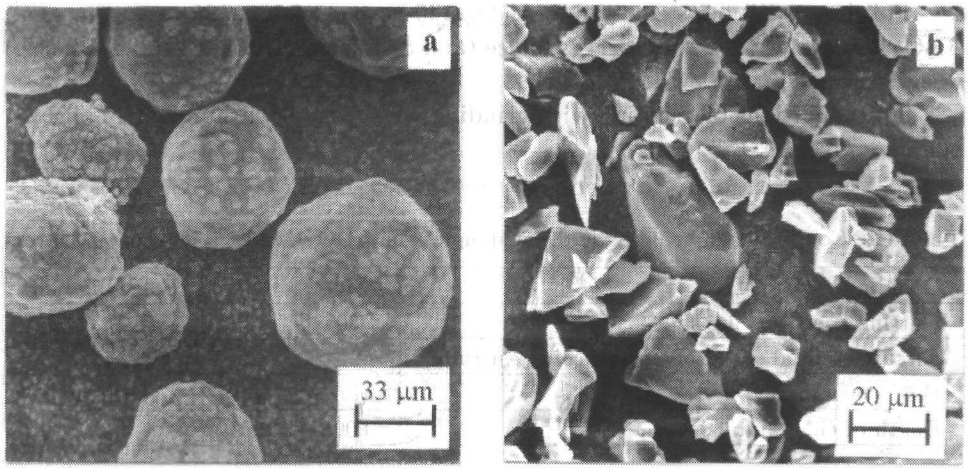


Fig. 1. Character of metallic and ceramic powder particles (SEM): a) NiAl (AMDRY 956), b) Al_2O_3 + 13% TiO_2 (AMDRY 6224).

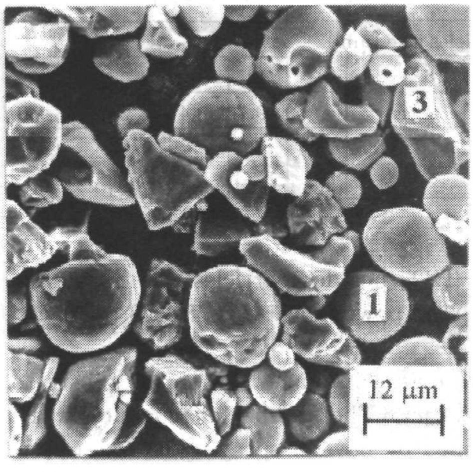
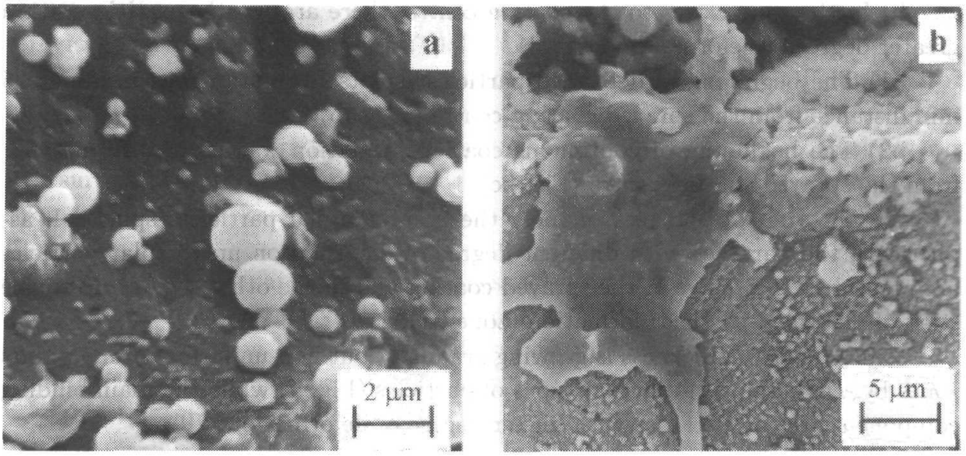


Fig. 2. Micrograph of Al_2O_3 + 13% TiO_2 powder particles after spraying to water (SEM): 1 – molten particles, 2 – partially molten particles, 3 – unmolten particles.

3. Results

A. Creation of coating

Typical appearance of substrate surface at ceramic powder spraying on a substrate for 5 seconds, when plasma gun had constant position against the substrate (spraying on one spot), is shown in Fig. 3.



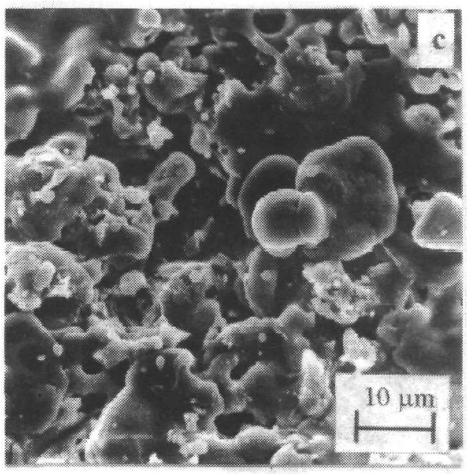


Fig. 3. Micrographs of substrate surface at different distances from the centre of the sprayed spot of ceramic layer (SEM): a – 47 mm, b – 25 mm, c – 13 mm.

The results of the substrate-surface study can be summarized as follows:

1. The zone of the plasma sprayed layer of Al_2O_3 + 13% TiO_2 can be principially divided into two main parts:

a) The part more distanced from the coating centre, characterized by the presence of small non-deformed, spherical and aspherical particles (Fig. 3a). The spherical shape of particles proves that these particles are molten in plasma jet, however, prior to their impingement on the substrate their thermal conditions and kinetic energy were insufficient for their deformation. Small, non-deformed particles (spherical, aspherical) of the size below 5 μm were observed even in 47 mm distance from the sprayed coating centre (Fig. 3a), and they are present in all zones of the coating.

b) In the zone closer to the coating centre, there are mostly particles with a greater degree of deformation (Fig. 3).

b1) The beginning of deformed particles (splats) formation was in about 25 mm distance from the sprayed coating centre (Fig. 3b).

b2) The beginning of continuous coating formation was in 13 mm distance from the sprayed coating centre (Fig. 3c).

2. All types of particles, namely the non-deformed particles (spherical, aspherical), the particles with different degree of deformation up to splat particles are present in the centre of the sprayed coating and in the other regions up to the start of deformed particles formation (zone b1).

3. The coating thickness is growing gradually but non-uniformly in individual zones by overlapping of different types of particles (Fig. 4) while the main binding component are the particles with higher degree of deformation.

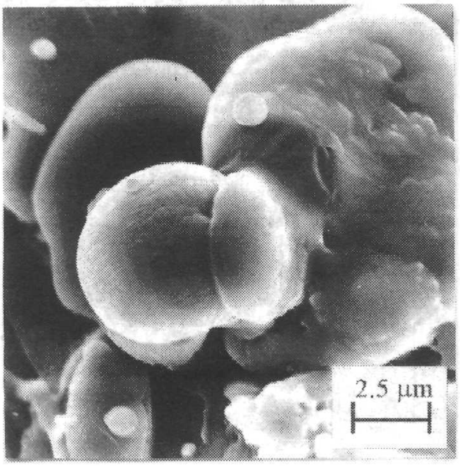


Fig. 4. Overlapping of particles in plasma spraying of Al_2O_3 + 13% TiO_2 powder (SEM).

4. Due to the irregular distribution and overlapping of particles with different degree of deformation on a rough surface (of substrate, in coating layer), the pores are present and the surface of the coating layer is rough.

B. Roughness development of NiAl and Al_2O_3 + 13% TiO_2 coating layers

The NiAl coating layer is deposited on the grit-blasted substrate surface prior to deposition of a ceramic layer. The change in surface roughness (*Ra*) in dependence on thickness of the NiAl and Al_2O_3 + 13% TiO_2 coating layer is shown in Fig. 5. The arithmetic mean of the substrate surface roughness from 10 measurements after corundum blasting was $Ra = 17.4 \pm 1.12$ μm. (Further, instead of "arithmetic mean of surface roughness from 10 measurements" we shall use an abbreviated form "surface roughness".) By a gradual deposition of the NiAl coating layer, with increasing thickness the surface roughness decreases and starting from 0.14 mm thickness, its stabilization in the interval of $Ra = 7.36 \pm 0.58 - 8.25 \pm 0.87$ μm takes place. By a gradual deposition of the Al_2O_3 + 13% TiO_2 coating layer on the surface of the NiAl coating layer, the surface roughness decreases and starting from 0.065 mm thickness, it is stabilized at the value $Ra = 3.28 \pm 0.11 - 3.42 \pm 0.08$ μm.

When the substrate surface roughness after grit blasting is lower, e.g. similar to the roughness of the NiAl layer from Fig. 5 ($Ra = 7.82 \pm 0.79$ μm), then, at gradual deposition of the NiAl coating layer, its surface roughness varies only slightly. Up to the thickness of 0.055 mm, it is in the interval of $Ra = 6.15 \pm 0.90 - 7.47 \pm 1.47$ μm as shown in Fig. 6.

Similarly as in the previous case (Fig. 5), with increasing thickness of the ceramic coating layer its surface roughness decreases and in the interval of layer thickness from 0.06 to 0.16, it is stabilized within the interval $Ra = 3.28 \pm 0.15 - 4.58 \pm 0.38$ μm (Fig. 6).

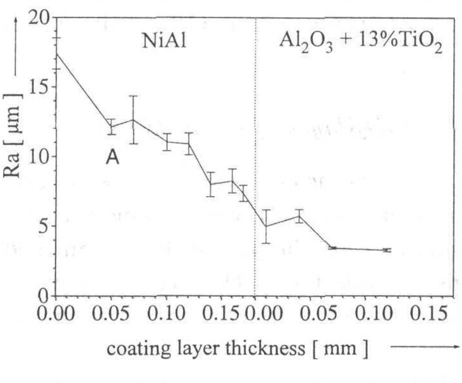


Fig. 5. Dependence of surface roughness course (Ra) on the thickness of NiAl and Al_2O_3 + 13% TiO_2 coating layers. Substrate surface roughness: $Ra = 17.4 \pm 1.12$ μm, substrate material: duralumin AlCu4Mg.

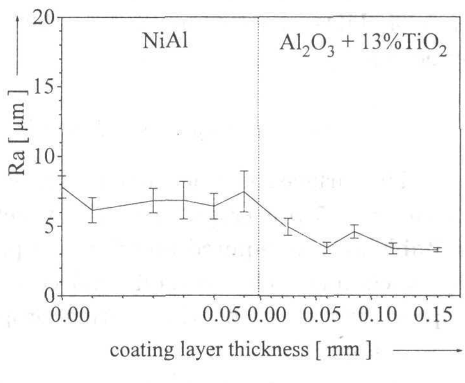


Fig. 6. Dependence of surface roughness course (Ra) on the thickness of NiAl and Al_2O_3 + 13% TiO_2 coating layers. Substrate surface roughness: $Ra = 7.84 \pm 0.79$ μm, substrate material: duralumin AlCu4Mg.

In the case when the substrate surface roughness after grit blasting is lower than the surface roughness of the NiAl layer (e.g. $Ra = 4.13 \pm 0.57$ μm), then with increasing thickness of the NiAl coating layer, its surface roughness also increases up to 0.035 mm thickness (Fig. 7). In the interval of the NiAl coating layer thickness of

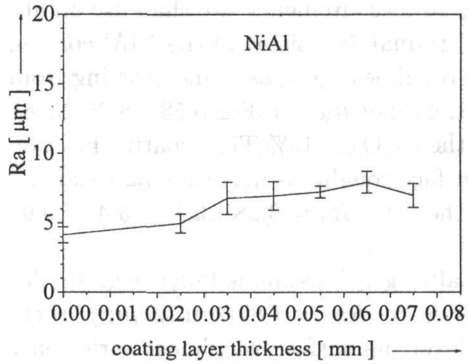


Fig. 7. Dependence of surface roughness course (*Ra*) on the thickness of NiAl coating layer. Substrate surface roughness: *Ra* = 4.13 ± 0.57 μm, substrate material: carbon steel 11 500.

0.035–0.075 mm, the surface roughness ranges within the interval $Ra = 6.78 \pm 1.17$ – 7.93 ± 0.78 μm.

The amount of NiAl powder supplied to the plasma jet was 9.3 g/min (Fig. 5, 6, 7). Only the first part of the NiAl coating layer (Fig. 5, position A) was sprayed on the substrate surface at powder transport of 25.7 g/min. This corresponds to the thickness of a deposited layer of 0.05 mm. The powder transport of Al_2O_3 + 13% TiO_2 powder supplied to the plasma jet was constant (19 g/min) in all experiments.

C. Surface roughness of Al_2O_3 + 13% TiO_2 layer after machining

The surface roughness of the plasma sprayed ceramic layer varies in the interval of Ra = 3–5 μm (Figs. 5, 6, 7). When the mentioned surface roughness is not suitable for the required function of a part surface then the part surface is finished by machining. The methods and conditions suitable for machining the coatings depend first of all on the coating properties. For ceramic coatings, grinding is mostly applicable.

Surface roughness of the Al_2O_3 + 13% TiO_2 coating layer after grinding and polishing at the conditions given in Tab. 2 are shown in Tab. 4. Thus it can be concluded that after polishing the ceramic layer with polishing belts of different grain size, the surface roughness is approximately similar and it is in the interval $Ra = 1.23 \pm 0.51$ – 1.67 ± 0.46 μm. After grinding the differences in surface roughness are even smaller ($Ra = 0.83 \pm 0.22$ μm – SiC, $Ra = 0.82 \pm 0.23$ μm – DIA, Tab. 4).

The appearance of the surface of the Al_2O_3 + 13% TiO_2 coating layer after plasma spraying, polishing, and grinding (in Tab. 4 marked as 2, 3, 7, 8) is shown in Fig. 8. The surface of the ceramic layer after plasma spraying (Fig. 8a) is formed of particles of different size and different degree of deformation, mutually overlapping and irregularly distributed as it was already mentioned.

Table 4. Substrate (duralumin AlCu4Mg) surface roughness after grit blasting and surface roughness of the ceramic coating layer after plasma spraying and machining

Characteristic surface	1	2	3	4	5	6	7	8
Ra [μm]	5.01 ± 0.29	3.16 ± 0.29	1.63 ± 0.54	1.67 ± 0.46	1.65 ± 0.64	1.23 ± 0.51	0.83 ± 0.22	0.82 ± 0.23

1 – substrate (duralumin AlCu4Mg) surface roughness after grit blasting,
2 – surface roughness of the ceramic coating layer after plasma spraying,
3 – surface roughness of the ceramic coating layer after polishing with a polishing belt Al_2O_3 – grain size 120 (100–125 μm),
4 – surface roughness of the ceramic coating layer gradually polishing with polishing belts Al_2O_3 – grain size 120 and 400,
5 – surface roughness of the ceramic coating layer after polishing with a polishing belt Al_2O_3 – grain size 400 (22–32 μm),
6 – surface roughness of the ceramic coating layer after gradually polishing with polishing belts – Al_2O_3 120 and SiC 240,
7 – surface roughness of the ceramic coating layer after grinding with a SiC grinding wheel (C4980K9V) – grain size 80 (160–200 μm),
8 – surface roughness of the ceramic coating layer after grinding with a diamond grinding wheel – grain size D 63/50 (50–63 μm).

The surfaces of the ceramic layer after polishing and grinding exhibit a similar character and consist of smooth and rough areas of different size and distribution (Fig. 8b,c,d).

4. Discussion

In the real conditions of plasma spraying, the plasma gun has not a constant position related to the substrate. This fact will affect the amount of particles impinging on a given substrate zone. The amount of small non-deformed particles on the surface of the substrate (coating layer) is also affected by the position of powder injector to the axis of plasma jet [8], spraying distance, cooling air, and plasma jet. However, some amount of small, non-deformed powder particles is always present. Their bonding to the substrate or coating layer is weaker, and their presence affects the adherence and cohesion characteristic as well as the porosity of the coating layer.

The mentioned results of surface roughness after plasma spraying (Fig. 5–9) show that the surface roughness of NiAl (AMDRY 956) and Al_2O_3 + 13% TiO_2 (AMDRY 6224) layers is stabilized after reaching a certain thickness and it stays in the interval around $Ra = 6$–8 μm and $Ra = 3$–5 μm for the NiAl and ceramic layer, respectively. The mentioned surface-roughness intervals do not depend on the substrate material (steel type 11 500, duralumin AlCu4Mg) and its surface roughness after grit blasting ($Ra = 4.13 \pm 0.57 \sim 17.4 \pm 1.12$ μm). In the case of

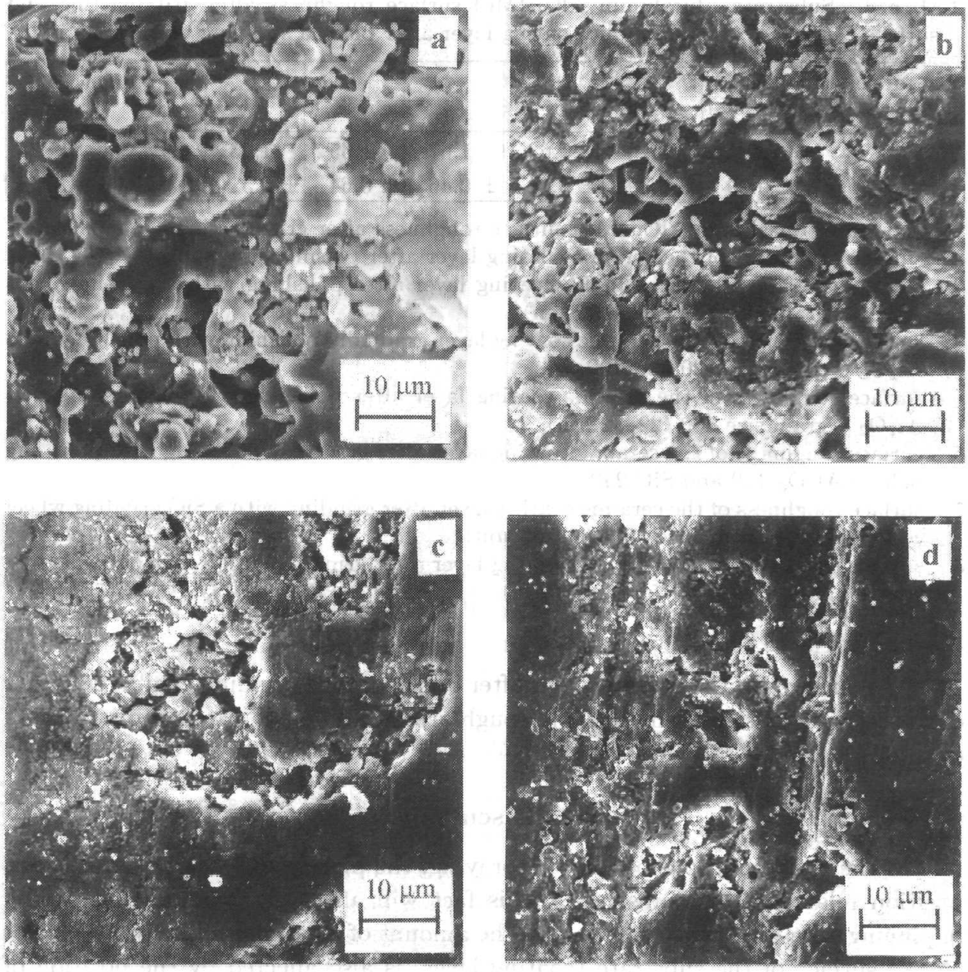
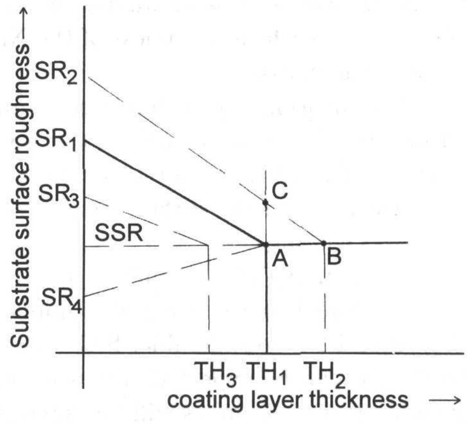


Fig. 8. Micrographs of surface of Al_2O_3 + 13% TiO_2 ceramic coating layer (SEM): a) after plasma spraying, b) after polishing with polishing belts (Al_2O_3 grain size 120), c) after grinding with a SiC grinding wheel type C4980K9V – grain size 80 (160–200 μm), d) after grinding with a diamond grinding wheel – grain size D 63/50 (50–63 μm).

the NiAl coating layer the roughness values were within the mentioned interval, even in the case of considerably different powder transport to the plasma jet (9.3 and 25.7 g/min).

The different values of "stabilized" surface roughness for the metallic and ceramic layer follow mainly from the different granularity of used powders (Tab. 3).

Fig. 9. Scheme of dependence of coating surface roughness on substrate surface roughness. SSR – stabilized surface roughness of a coating layer.



Regarding the evaluation of the effect of surface roughness of substrate surface on the surface roughness of coating surface [5] and the mentioned experimental results, it is necessary to point out, that the relationship between the roughness of the coating layer and substrate will depend mainly on:

a) difference between the surface roughness of substrate surface and the stabilized surface roughness of the coating layer surface,

b) required thickness of the deposited layer.

Let us suppose in the first approximation that the surface roughness of a coating layer decreases from the initial surface-roughness value of the substrate surface (SR_1) to the value of stabilized roughness of the coating surface (SSR) according to Fig. 9 and attains it at the point A. The corresponding thickness of a sprayed layer is TH_1. When the surface roughness of the substrate surface is greater (SR_2), stabilization of surface roughness of the coating layer is achieved at greater thickness of the coating layer TH_2 (point B). Then, for all values of substrate surface roughness greater than SR_1, the surface roughness of the coating layer is affected by the surface roughness of the substrate, since the surface roughness of the coating layer at the required coating thickness TH_1 is the greater the greater is the roughness of the substrate surface SR_2 (point C, Fig. 9).

For the surface roughness of the substrate layer from the interval $\langle SSR, SR_1 \rangle$ and required thickness of the coating layer TH_1, the surface roughness of the coating layer does not depend on the surface roughness of the substrate surface, since the stabilized value of the surface roughness of the coating layer is attained already at lower values (TH_3, Fig. 9) than the required thickness of the coating layer TH_1.

Thus, it can be concluded that when the required coating thickness of a NiAl layer is $TH_1 = 0.1$ mm and the surface roughness course of the NiAl layer surface the same as shown in Fig. 5, the surface roughness of the NiAl layer depends on the substrate surface roughness. In case the stabilized value of the surface roughness of the NiAl layer is attained already at lower coating thickness than $TH_1 = 0.1$ mm (Fig. 6), the surface roughness of the NiAl layer is not dependent on the substrate surface roughness.

The mentioned principle can be applied also in the case when the substrate surface roughness is lower than the stabilized roughness of the NiAl layer surface ($SR_4 < SSR$), Fig. 7, and also for evaluation of the effect of surface roughness of the NiAl layer on the surface roughness of a ceramic layer surface in the case of a two-layer coating.

For grinding the ceramic layer of Al_2O_3 + 13% TiO_2 we used the grinding wheels with siliconcarbide and diamond abrasive grains. Difference in hardness of SiC and DIA is considerable: SiC – 2400, DIA – 7000 in the Knoops scale [9]. Due to that, it can be expected that also the grinding efficiency and conditions of the surface layer of ceramics will be different.

Some results of the mentioned differences between grinding with DIA and SiC grinding wheels are visible on the character of the ceramic layer surface. After grinding with DIA grinding wheel, fine grooves oriented in grinding direction are visible on the ceramic layer surface. Surface of the ceramic layer after SiC grinding is smooth and some cracks are present (Fig. 8). The crack formation is a result of high thermal loading with SiC grinding wheel because of wear of SiC grains due to their smaller hardness than is the hardness of DIA grains and cutting conditions used (cutting speed: 30 m/s, grinding without cooling).

Typical micrographs of the ceramic layer after plasma spraying, polishing, and grinding are in Fig. 8. Surfaces of the ceramic layer after polishing and grinding are similar and consist of smooth and rough areas.

The smooth areas are the result of a cutting process, however, the rough ones are of different origin. By polishing, we usually remove about 0.03–0.04 mm from the ceramic layer. In that case, the rough areas are mostly the surface areas of the ceramic-layer surface after plasma spraying from which the tops of unevennesses have been removed due to the action of abrasive grains.

At grinding, the surface layer of a certain thickness is removed and the coarse areas are mostly the areas of pores inside the ceramic layer. By a gradual grinding off from the layer of ceramic material some pores are removed, some are disclosed. However, the pore areas are always present.

The surface roughness of the ceramic layer after grinding with SiC and DIA grinding wheels by the given grinding conditions is actually the same (Tab. 3) in spite of the fact that the size of abrasive grains of SiC grinding wheel is greater (160–200 μm) than that of DIA grinding wheel (50–63 μm). These results principally agree with the results of work [10] where by grinding of the ceramic layer of Al_2O_3 + 13% TiO_2, at the cutting speed $v_{DIA} = 30$ m/s, $v_{SiC} = 20$ m/s, depth of cut $a = 0.005$ mm, and size of abrasive grains SiC: 500 μm, DIA: 80–100 μm, the measured surface roughness was $Ra_{SiC} = 1.0$ μm and $Ra_{DIA} = 1.7$ μm. Due to higher hardness, the abrasive diamond grains remove the ceramic layer easier, at lower temperature, and causing less damage than the SiC grains. Therefore, with respect to possible damage of a ceramic layer, it is more suitable to use diamond grinding wheel [3], or when using the SiC grinding wheel, it is recommended mainly to reduce the cutting speed to v_k = 10–15 m/s, to use a cooling liquid [10], to employ small depth of cut and properly dressed SiC grinding wheel.

5. Conclusions

The main results of work aimed at study of a two-layer NiAl + (Al_2O_3 + 13% TiO_2) coating can be summarized as follows:

1. The study of character of Al_2O_3 + 13% TiO_2 powder particles and their distribution has shown that the ceramic coating layer is formed gradually, by overlapping of particles of different size and deformation degree which are irregularly dissipated on the substrate surface. The result of this process is a layer containing the pores and its surface is rough.

2. The surface roughness of metallic and ceramic coating layer depends mainly on the powder granularity. In the given conditions it is stabilized at the values within the interval of Ra = 6–8 μm (NiAl) and Ra = 3–5 μm (Al_2O_3 + 13% TiO_2). The effect of substrate surface roughness upon the surface roughness of the NiAl layer depends on the difference between the surface roughness of the substrate surface and stabilized surface roughness of the NiAl layer, and on the required thickness of the NiAl layer. The same is valid also for the couple: NiAl layer – Al_2O_3 + 13% TiO_2 layer.

3. If the attained surface roughness of the ceramic layer (around 3–5 μm) is not suitable for a desired application, the surface of the ceramic layer is finished by polishing or grinding. In the selected machining conditions the surface roughness of the ceramic layer after polishing was within the interval of Ra = 1–2 μm and after grinding with SiC and DIA wheel it was Ra = 0.8–0.9 μm. In the case when even lower values of surface roughness of the ceramic layer are requested, it can be attained by altering the grinding conditions or by use of diamond grinding wheel with smaller dimensions of abrasive grains.

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