IOP Conf. Series: Materials Science and Engineering **91** (2015) 012048 doi:10.1088/1757-899X/91/1/012048

On the Problem of Wear Resistant Coatings Separation From Tools and Machine Elements

S I Petrushin[1], R H Gubaidulina[1,2], S V Gruby[2,3] and A V Likholat[1,4]

[1]Yurga Institute of Technology, TPU affiliate
Kemerovo Region, Yurga, 26, Leningradskaya RUS
[2]Moscow State Technical University by N.E. Bauman
Moscow, 5, 2nd Baumanskaya RUS

E-mail[1]: psi@tpu.ru, E-mail[2,4]: victory_28@mail.ru, E-mail[3]: gru@bmstu.ru

Abstract. The article considers separation of wear resistant coatings of tool and engineering materials which arises both during coating fabrication and use of the product. The cause of this phenomenon is assumed to be related to thermal residual stresses generating on the coating-substrate border. These stresses have been analyzed and methods are provided to calculate it after produced composite material is cooled down from the temperature of coating synthesis to the ambient temperature. A no-fracture condition has been stated in relation to coating-substrate thicknesses, temperature differences and physical and mechanical properties of combined materials. The issue of intermediate layer incorporation with pre-set parameters has been discussed. A co-effect of thermal residual and functional stresses on the strength of the boundary layer has been considered when heating, tension and compression of a product with wear resistant coating. Conclusions have been made, as well as recommendations to improve fracture strength of products with thin wear resistant coatings.

1.Introduction

Wear resistant coatings layered on the surfaces of tool and engineering materials are widely applied in mechanical engineering in order to improve frictional surface layer life along with retention of strength characteristics of the product. For instance, leading companies [1, 2] coat high-speed steel and hard alloy cutting edges with variously combined thin layers of refractory material carbides and nitrides and aluminum oxide (TiC, TiN, Al_2O_3 etc.). Here, the total thickness of coating doesn't exceed 10 – 20 μm. If this value is exceeded a coating gets brittle and can separate both under action of functional stresses and when coating layers [3,4]. A similar phenomenon can also appear when surfacing, spraying, chrome or nickel plating and during some other processes with a distinguished border between layers (there is no significant diffuse zone). When breaking away interlaminar cracks arise on coating – base material (substrate) border. We consider a general approach to solve the problem of fracture strength of coating in terms of thermal residual stresses analyzed and stated in papers [5-8].

2 Results and Discussion

Calculation of thermal residual stress in laminated composite materials.

A product with a coated surface is a two-layer composite material where a surface layer is much thinner than a substrate. The strength of multi-layer composite materials depends not only on ultimate strength of layer materials but on interlaminar strength. It is often the strength of two adjacent layers that restricts integrity of a composite. It is caused by product heating up to a significant temperature ($T_И$) when composite material manufacturing. After sintering, surfacing, coating, layer-by-layer synthesis a composite is cooled down up to the ambient temperature (T_O). Herewith, thermal residual stresses arise on the border of two adjacent layers because of different linear expansion coefficients. If it exceeds the ultimate strength of any layer material cold interlaminar cracks appear and a composite material gets improper for this product.

If thermal residual stresses are smaller than the ultimate strength of layer materials monolithic nature of a composite is assured, however, it can reduce strength properties of a product. The layer of material with a bigger coefficient of linear expansion tends to decrease its dimensions more than the layer with a smaller coefficient of linear expansion. As the result, the first layer will be stretched by the second one and it will be pressed by the first one. In material with a bigger coefficient of linear expansion thermal tension residual stresses arises, and in material with a smaller coefficient of linear expansion there are compressive thermal residual stresses [4].

Let us consider a two-layer composite material synthesized at temperature difference $\Delta T = T_И - T_O$ and subject to thermal residual stresses only (Fig.1). The coefficient of linear expansion of material 1 is α_1, its coefficient of elasticity is E_1 and Poisson's ratio is μ_1, those of material 2 are α_2, E_2 and μ_2, respectively. We consider first the case, when $\alpha_1 \succ \alpha_2$. As the thickness of a single layer in a composite product is far smaller then its length and width, the state of two-dimensional stresses will arise in it when cooling down, Hook's law for it is as follows [9].

For layer 1 (tension) - $\sigma = \dfrac{\varepsilon E_1}{1-\mu_1}$; (1)

For layer 2 (compression) - $\sigma = \varepsilon E_2 (1-\mu_2)$. (2)

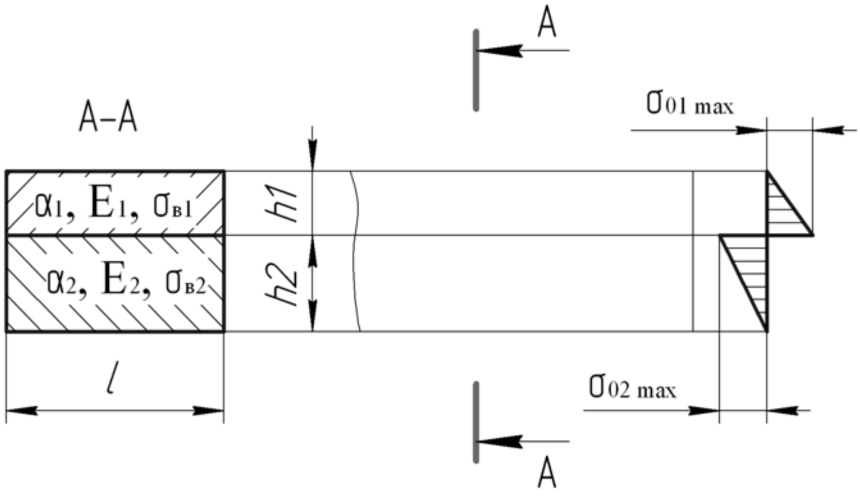

Figure 1. A diagram of two-layer composite material subject to thermal residual stresses only ($\alpha_1 \succ \alpha_2$).

For lack of external stresses maximum thermal residual stresses $\sigma_O^{\max}$ will be on the border of layers. Thermal residual stresses on the upper surface of layer 1 and on the lower surface of layer 2 equal to zero, and inside the layers they are distributed linearly (see Fig.1). Let us denote the cross-section area of layer 1 as $F_1 = bh_1$, and that of layer 2 as $F_2 = bh_2$, where b is the width of layers, h_1 and h_2 their thicknesses, the condition of equilibrium of forces provided that composite material on the border is uniform is as follows

$$\frac{1}{2}\sigma_{O1}^{\max} bh_1 = \frac{1}{2}\sigma_{O2}^{\max} bh_2$$

Hence,
$$\sigma_{O2}^{\max} = \sigma_{O1}^{\max}\frac{h_1}{h_2} \tag{3}$$

The absence of thermal cracks on border of layers in a composite material is to be assured by the condition of deformations equality [6]. In layer 1 deformation caused by thermal cooling down $\varepsilon = \alpha\Delta T$ is opposite in direction to residual stresses caused by thermal residual stresses, in layer 2 these deformations are added. Therefore, in terms of equations (1) and (2) we have:

$$\alpha_1\Delta T - \frac{\sigma_{O1}^{\max}(1-\mu_1)}{E_1} = \alpha_2\Delta T + \frac{\sigma_{O2}^{\max}}{E_2(1-\mu_2)} \tag{4}$$

For the case under consideration ($\alpha_1 \succ \alpha_2$) maximum tension stresses in layer 1 are the most disadvantageous conditions in terms of interlaminar cracks arising in a composite material. It is calculated according to (4) and (3) as follows:

$$\sigma_{O1}^{\max} = \frac{\Delta T(\alpha_1 - \alpha_2)}{\frac{1-\mu_1}{E_1} + \frac{1}{E_2(1-\mu_2)}\frac{h_1}{h_2}} \tag{5}$$

We denote the ultimate tension strength of layer 1 material as σ_{b1}, and the safety factor as $k \succ 1$ in view of deviated real physical and mechanical parameters of layer materials in a composite from the designed parameters ($k_{\min} \approx 1{,}5$). Then the condition of fracture strength in a two-layer composite material (see Fig.1), cooled down by temperature difference ΔT and not subject to operating thermal and functional stresses, is written as follows:

$$\frac{\sigma_{b1}}{k} \geq \frac{\Delta T(\alpha_1 - \alpha_2)}{\frac{1-\mu_1}{E_1} + \frac{1}{E_2(1-\mu_2)}\frac{h_1}{h_2}} \tag{6}$$

It is worth noting that the condition (6) enables the first phase of designing a composite and a coated composite aimed at assuring their uniformity when manufacturing. For this purpose we express layer thicknesses relation in terms of equation (6):

$$\frac{h_1}{h_2} \geq \left[E_1\Delta T(\alpha_1 - \alpha_2)k - (1-\mu_1)\sigma_{b1}\right]\frac{E_2(1-\mu_2)}{E_1\sigma_{b1}} \tag{7}$$

Inequation (7) sets the limit for layer thicknesses relation in a two-layer composite, after it's exceeded interlaminar thermal cracks will arise in the lay.

Similarly to the case, when $\alpha_1 \prec \alpha_2$, the following condition of fracture strength is obtained:

$$\frac{h_1}{h_2} \leq \frac{\sigma_{b2}E_2}{\left[\Delta T(\alpha_2 - \alpha_1)kE_2 - (1-\mu_2)\sigma_{b2}\right]E_1(1-\mu_1)} \tag{8}$$

where σ_{b2} - ultimate strength of the second layer material

When deducing the inequation (8) we took into consideration that after cooling down layer 1 will be pressed and layer 2 – stretched.

Breaking away after coating.

In terms of mentioned above information we consider the issue of coatings breaking away in respect to technologies of soldering and surfacing. Equations (7) and (8) preset the condition of a coating non-breaking away from the substrate unless a composite is exposed to an external stress. Figure 2 provides an example of fracture strength borders calculated according to (9) and (10) for a two-layer composite consisting of steel 60 ($\sigma_b = 1500$ MPa; $\alpha = 11{,}5 \cdot 10^{-6}\, 1/{}^oC$; $\mu = 0{,}3$; $E = 218500$ MPa) and tungsten-cobalt hard alloy BK8 ($\sigma_b = 1590$ MPa; $\alpha = 5{,}1 \cdot 10^{-6}\, 1/{}^oC$; $\mu = 0{,}23$; $E = 598400$ MPa). It demonstrates that the relation of layer thicknesses depends significantly on operating temperature of a composite manufacturing. There will be no thermal cracks when heating less 500^oC, it conforms to conditions of low-temperature soft soldering. If the temperature of the process is higher (hard soldering, powder sintering, surfacing), the relation of thicknesses of composite layers are to be taken into consideration. Figure 2 demonstrates that when $\alpha_1 \succ \alpha_2$ (steel coated hard alloy substrate) the thickness of the upper layer of a composite increases in direct proportion to the rise of operating temperature, and when $\alpha_1 \prec \alpha_2$ (hard alloy coated steel) it decreases according to a hyperbola dependence.

Therefore, coated composites can have thermal residual stresses inside their structure before they are used; the value of these stresses depends on the operating temperature of composite manufacturing and on the difference of thermal linear expansion coefficients of layer materials. One should take it into consideration when designing coated products because functional stresses being algebraically added to thermal residual stresses can cause either coating separation or increase in the strength of coating-substrate cohesion.

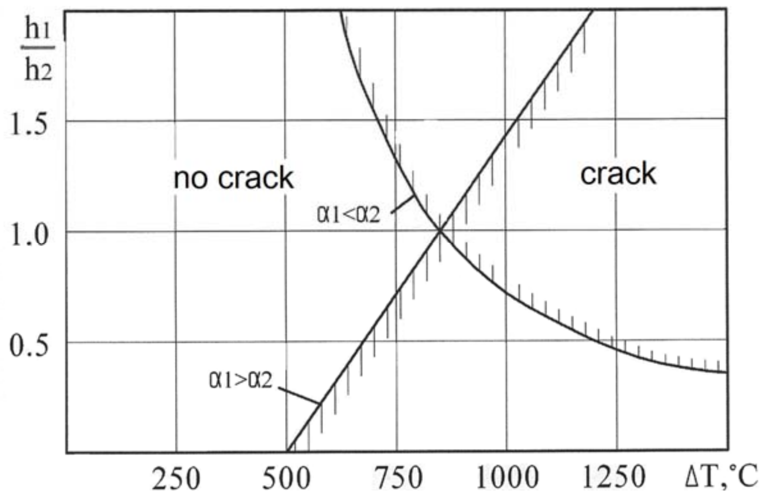

Figure 2. Fracture strength borders for a two-layer composite.

It is worth mentioning that after a two-layer composite is cooled down thermal residual stresses arise in the layer of steel in both cases, and thermal compression residual stresses grow in hard alloy layer, that is, we have a preliminary stressed material.

Layered composites whose coating and substrate are made of the same material have been studied so far. Provided that thickness relations resulted from conditions (7) and (8) are improper for composite functioning, the purpose of designing can be achieved by introducing between the layers an interlaminar layer being a mixture of source materials (two-layer coating). The simplest way to produce composites of this kind is powder metallurgy. In terms of mixture laws [10], physical and mechanical properties of an interlaminar layer are determined as follows:

- ultimate strength

$$\sigma_{bc} = \sigma_{b1}\upsilon_1 + \sigma_{b2}\upsilon_2 = \sigma_{b2} - \upsilon_1(\sigma_{b2} - \sigma_{b1});$$

- coefficient of linear expansion

$$\alpha_c = \alpha_1\upsilon_1 + \alpha_2\upsilon_2 = \alpha_2 - \upsilon_1(\alpha_2 - \alpha_1);$$

- Poisson's ratio

$$\mu_c = \mu_1\upsilon_1 + \mu_2\upsilon_2 = \mu_2 - \upsilon_1(\mu_2 - \mu_1);$$

- modulus of elasticity

$$E_c = E_1\upsilon_1 + E_2\upsilon_2 = E_2 + \upsilon_1(E_1 - E_2)$$

where $\upsilon_1 = V_1/V_c$ - volume concentration of material 1 in the mixture;
$\upsilon_2 = V_2/V_c$ - volume concentration of material 2 in the mixture, whereas $\upsilon_1 + \upsilon_1 = 1$

Let us substitute these values for the criterion of fracture strength (7). Then, a condition of no cold thermal cracks between the upper layer of coating and mixture is as follows:

$$\frac{h_1}{h_c} \geq [E_1\Delta T(\alpha_1 - \alpha_c)k - (1-\mu_1)\sigma_{b1}]\frac{E_c(1-\mu_c)}{E_1\sigma_{bc}} \tag{9}$$

The same condition for the mixture and substrate material:

$$\frac{h_c}{h_2} = [E_c\Delta T(\alpha_c - \alpha_2)k - (1-\mu_c)\sigma_{bc}]\frac{E_2(1-\mu_2)}{E_c\sigma_{bc}} \tag{10}$$

If a grade composite is produced according to the principle $\alpha_1 \prec \alpha_C \prec \alpha_2$ we have the similar conditions of fracture strength assuring obtained on the basis of equation (8)

$$\frac{h_1}{h_c} \leq \frac{\sigma_{bc}E_c}{[\Delta T(\alpha_c - \alpha_1)kE_c - (1-\mu_c)\sigma_{bc}]E_1(1-\mu_1)}: \tag{11}$$

$$\frac{h_c}{h_2} \leq \frac{\sigma_{b2}E_2}{[\Delta T(\alpha_2 - \alpha_c)kE_2 - (1-\mu_2)\sigma_{b2}]E_c(1-\mu_c)}. \tag{12}$$

Therefore, a monolithic nature of grade composite with interlaminar layers of multilayer coating can be obtained by varying volume concentrations of adjacent materials in the mixture with equations (9) – (12).

Functionally stressed breaking away

If a coated product is used under thermal functional stresses the relation of coating and substrate thicknesses can be selected on the ground of formulae (7) and (8), where ΔT is the difference of coating synthesis temperature and functional temperature. If coating is stressed by forces, for instance, friction force, the problems of strength of materials are to be resolved according to the loading conditions.

Let us consider a two-layer composite with b-wide rectangular cross-section synthesized at temperature difference $\Delta T = T_H - T_O$ and subject both to tension force P and thermal residual stresses. Top h_1-thick material has a coefficient of linear expansion α_1, modulus of elasticity E_1 and Poisson's ratio μ_1 while bottom h_2-thick material has parameters: α_2, E_2 and μ_2, whereas $\alpha_1 \prec \alpha_2$. As the result of force P action there is tension stress in the bar

$$\sigma_p = \frac{P}{(h_1 + h_2)\cdot b} \tag{13}$$

For the case under consideration according to formula (7) maximum thermal residual stresses can be calculated on the upper surface of the bottom layer and according to formula (8) – on the lower surface of the top layer in a two-layered composite. If this residual stress is added to functional tension stress in terms of (13), the total stresses on the border of layers will equal to

- for layer 1 - $$\sigma_{\Sigma 1} = \frac{\Delta T(\alpha_1 - \alpha_2)}{\frac{1}{E_1(1-\mu_1)} - \frac{1-\mu_2}{E_2} \cdot \frac{h_1}{h_2}} + \frac{P}{(h_1 + h_2)\cdot b}; \quad (14)$$

- for layer 2 - $$\sigma_{\Sigma 2} = \frac{\Delta T(\alpha_2 - \alpha_1)}{\frac{1-\mu_2}{E_2} - \frac{1}{E_1(1-\mu_1)} \cdot \frac{h_2}{h_1}} + \frac{P}{(h_1 + h_2)\cdot b}. \quad (15)$$

In formula (14) the first summand will be negative ($\alpha_1 \prec \alpha_2$), in (15) – positive. Therefore, under action of a force compressive thermal residual stresses in coating will be compensated through tension stresses caused by an external force. On the contrary, in layer 2 (substrate) these stresses will sum up and probably cause a crack on the border of the layers. Then, the condition of fracture strength of a two-layer coated composite cooled down by the temperature difference ΔT and stressed by tension force P is as follows

$$\frac{\sigma_{b2}}{k} \geq \frac{\Delta T(\alpha_2 - \alpha_1)}{\frac{1-\mu_2}{E_2} - \frac{1}{E_1(1-\mu_1)} \cdot \frac{h_2}{h_1}} + \frac{P}{(h_1 + h_2)\cdot b} \quad (16)$$

If a coated composite is compressed the equation (14) is critical and on its ground the condition of fracture strength can be deduced which is similar to equation (16).

Summary

1. When designing wear resistant coated products a probability of coating separation is to take into consideration. It is caused by thermal residual stresses arising between coating and substrate when they are technologically heated and an obtained composite is cooled down.
2. For coatings with a distinct border with the product thermal residual stresses depend on physical and mechanical properties of coating and substrate materials (coefficient of linear expansion, modulus of elasticity, Poisson's ratio, and ultimate strength), temperature of product heating when synthesizing, and material thicknesses relation.
3. Obtained no-cracks conditions make it possible to match the thickness of coating with its production technology even at the stage of designing composite materials.
4. The problem is resolved to calculate fracture strength of thermally and functionally stressed layered composite materials, and depends on the type of stress coated products are subject to (tension, compression, bending etc.)

References

[1] Tyalina L N, Minaev A M and Pruchkin V A 2011*Tambov GOU TGTU* 80
[2] Bouznik B M, Fomin V M and Alkhimov A P 2005 *Novosibirsk Publishing House of SB RAS* 260.
[3] Vereshchaka A S 1993 *Machinebuilding.* 336
[4] Petrushin S I, Saprykin A A and Dureev V V 2014 *Tomsk TPU Publishing* 205
[5] Saprykina N A and Saprykin A A 2013 *Appl. Mechan. and Mater* **379** 56I
[6] Petrushin S I 2013 *Appl. Mechan. and Mater* **379** 100
[7] Saprykina N A and Saprykin A A, 2014 *Appl. Mechan. and Mater*I **1040** 808
[8] Petrova. V A, Bakanov A A and Walter A V 2014 *Appl. Mechan. and Mater.* **682** 431
[9] Mechanical engineering. Encyclopedic reference book 1948 Engineering calculations in mechanical engineering *Mashgiz* 457
[10] Bazhenov S L, Berlin A A, Kul'kov A A, Oshmyan V G 2010 *Publishing house «Intellect»* 352