Investigation on Thermal Stress-Strain State in Multilayered Composites during Nickel Aluminide Coatings Formation

VICTOR SHMORGUN*, ARTEM BOGDANOV, MIKHAIL TRUNOV and ALEXANDR TAUBE
Volgograd State Technical University
Materials Science chair
Lenin avenue, 28, 400005, Volgograd
RUSSIAN FEDERATION
*Corresponding email: mv@vstu.ru

Abstract: In this study multi-layered steel-nickel-aluminum composite with intermetallic interlayers was obtained using complex process which included explosion welding and heat treatment. Strength properties of the diffusion $NiAl_3$+Ni_2Al_3 interlayer under thermal stress were investigated. The thickness value of diffusion interlayer as well as thickness ratios of composites components contributing to the rupture of the intermetallic interlayer during thermal loading were identified via standard method and verified using FEM simulation. The calculated results correspond with the experimental investigations. The interlayer rupture resulted in the formation of Ni/Ni_2Al_3 coating on steel.

Key–Words: Laminated composites, steel, aluminum, coating, explosion welding, nickel aluminide

1 Introduction

Gas and steam turbine components are usually made of steel and can undergo temperatures higher than 700 °C. One of the perspective methods of the components protection is the formation of Al-Ni intermetallic coatings on the surface of such parts. According to recent studies complex methods of such coatings formation are applied alongside with the traditional ways [1–6]. The complex methods allow creating multilayered (Ni/Ni_2Al_3) coating structures [7–10] where each layer performs a special task. The Ni layer prevents the penetration of Al atoms into steel layer and provides high adhesion of the coating to the substrate, while the nickel aluminide protects the base material from oxidation due to the formation of robust Al_2O_3 on its surface.

In this study a new approach of the multilayered coatings manufacture was developed. The approach includes the following steps:

1. The joining of nickel to steel via explosion welding (EW).
2. Pressure treatment of the steel/nickel bimetal.
3. Explosion joining of Al sheet to the nickel side of the steel/nickel composite.
4. Heat treatment of the obtained composite, which leads to the formation of intermetallic layer due to solid state diffusion.

Such sequence of operations contributes to high coating/base material bond strength and can be applied to manufacture the components of the special shape. The present study aims to investigate the impact of the layer width ratio on the thermal stress which occurs during the process of cooling of the composite after diffusion heat treatment.

2 Materials and experiments

In this study 12X11VMF steel, Np2 nickel alloy and AA1135 aluminum alloy were used to fabricate the composite for investigations. Chemical composition of materials used in this study is presented in table 1

The conditions of EW to join 12X11VMF and Np2 plates were chosen to obtain a wavy interface of the bond area. The bond also included molten zones in its structure. The thickness of 12X11VMF and Np2 plates was 10 and 1 mm respectively.

Subsequent pressure treatment included hot rolling, performed on twin roll mill at 850 °C with the total 57% thickness reduction which resulted Np2 layer to be 0.1 mm thick.

The joining of AA1135 plate to 12X11VMF/Np2 bimetal was carried out via EW. The conditions were chosen to avoid wavy interface formation. AA1135 plates with various thickness values in the range between 0.7-10 mm were used in this study.

To obtain intermetallics in the composites structure the 3-metal was heat treated at 600 °C for the

Table 1: Chemical composition of the materials used in this study

Material	Chemical composition, wt. %						
12X11VMF	C, 0.09-0.15	Si, 0.3-0.7	Mn, 0.5-1.1	Cr, 10-12	Ni, 0.6-0.9	Mo, 0.6-0.9	Fe, >85
AA1135	Fe, 0.3	Mn, 0.025	Ti, 0.15	Cu, 0.05	Mg, 0.05	Zn, 0.1	Al, >99.3
Np2	C, <0.02	Cu, <0.25	Fe, <0.4	Mg, <0.05	Mn, <0.35	Ni, >99.5	

range from 1 to 10 hours.

Metallographic investigations were performed on a motorized optical microscope Olympus BX61.

3 Results and discussion

According to previous study [11] heat treatment of the 3-layered steel/Ni/Al composite contributes to the formation of the continuous interlayer between Ni and Al. The interlayer has two intermetallics in its structure: Ni_2Al_3 adjacent to Ni side and $NiAl_3$ adjacent to Al side. The separation of the AA1135 layer was observed only in some cases during subsequent to heat treatment cooling of the composite. The separation was caused by the rupture of the adjacent to Al $NiAl_3$ intermetallic if the total thickness of the diffusion interlayer exceeded 30 μm. The most common reason for rupture is thermal stress, which occurs in the interlayer boundary due to differences in thermal expansion coefficient values of its components. To assess the thermal stress value, the standard model, proposed by Timoshenko was applied. The approach suggested the following assumptions:

1. The thickness values of Np2 and intermetallic layer are insufficiently small related to the thickness of steel and AA1135 layers, therefore the impact of thin layers was not considered.

2. Temperature field in steel and AA1135 is uniformly distributed.

3. Both thermal expansion coefficient and elastic modulus do not depend on temperature.

The design scheme of the composite is presented on figure 1.

To define the neutral axis position, consider deformation of the bimetallic element under bending moment M_x. The element is assumed to be thin with uniaxial stress distribution in it and undergoing no temperature impact.

According to Kirchhoff Hypothesis the normals remain unstretched and therefore the strain is given by:

$$\epsilon_x = \frac{y}{\rho_x}, \tag{1}$$

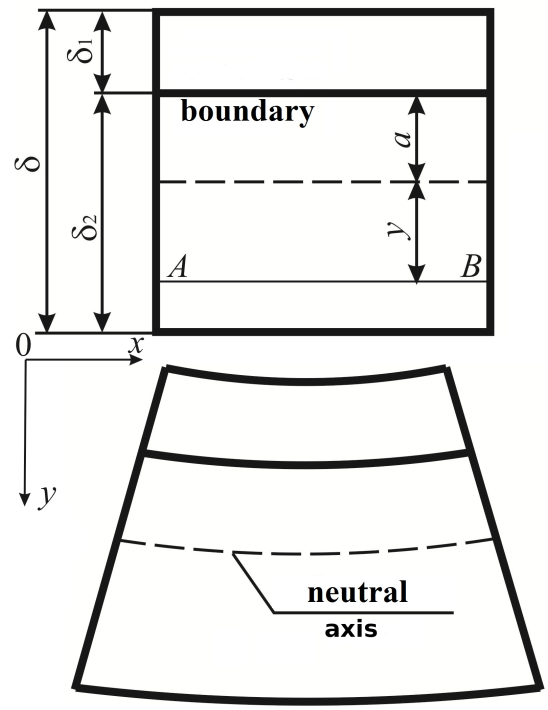


Figure 1: Bimetallic element before and after heating

where y denotes the distance from the neutral axis (fig. 1); ρ_x – denotes the curvature of the element at its neutral axis.

According to Hooke's law the stress values at upper and bottom layers of the plate are given by:

$$\begin{aligned} \sigma_{x_1} &= \epsilon_x E_1 = \frac{yE_1}{\rho_x}, \\ \sigma_{x_2} &= \epsilon_x E_2 = \frac{yE_2}{\rho_x}. \end{aligned} \tag{2}$$

where E_1 and E_2 – elastic modulus of layers.

The neutral axis position can be found considering the neutral axis load N to be equal to zero. The neutral axis load is equal to the sum of integrals of σ_x over the thickness of bottom and upper layers:

$$\begin{aligned} N &= \int_{-(\delta_1+a)}^{-a} \sigma_{x_1}\, dy + \int_{-a}^{(\delta_2-a)} \sigma_{x_2}\, dy = \\ &= -\frac{E_1\delta_1}{\rho_x}\left(\frac{\delta_1}{2}+a\right) + \frac{E_2\delta_2}{\rho_x}\left(\frac{\delta_2}{2}-a\right) = 0, \end{aligned} \tag{3}$$

which implies:

$$a = \frac{E_2\delta_2^2 - E_1\delta_1^2}{2\left(E_1\delta_1 + E_2\delta_2\right)}. \tag{4}$$

here δ_1 and δ_2 – denote thicknesses of layers, a – distance between the bond and the neutral axis.

The bending moment M_x is the sum of integrals of the product of σ_x and y over the thickness of bottom and upper layers:

$$M_x = \int_{-(\delta_1+a)}^{-a} \sigma_{x_1} y\,dy + \int_{-a}^{(\delta_2-a)} \sigma_{x_2} y\,dy, \tag{5}$$

thus considering (2):

$$M_x = \frac{E_1J_1 + E_2J_2}{\rho_x}, \tag{6}$$

where J_1 and J_2 – denote moments of inertia per unit width of cross section of upper and bottom layers with respect to the neutral axis:

$$J_1 = \frac{(\delta_1 + a)^3 - a^3}{3}, \quad J_2 = \frac{(\delta_2 + a)^3 - a^3}{3}. \tag{7}$$

Then considering equation (6), the equation (2) can be presented as:

$$\sigma_{x_1}^M = \frac{M_xE_1y}{E_1J_1 + E_2J_2}, \quad \sigma_{x_2}^M = \frac{M_xE_2y}{E_1J_1 + E_2J_2}. \tag{8}$$

Now consider the bimetallic element is cooled from the recrystallization temperature of aluminum to room temperature, thus the change in temperature $\Delta t = (273-20) - 0.4T_{Melt}^{Al} \approx -80\,^\circ\mathrm{C}$ (here T_{Melt}^{Al} – denotes melting point of Al) and undergoes the bending moment M_x'. The value of M_x' is chosen to contribute the curvature to be equal to zero. Thus the elongation at the upper layer is equal to:

$$\epsilon_1 = \frac{\sigma_{x_1}'}{E_1} + \alpha_1\Delta t, \tag{9}$$

while the elongation at the bottom layer:

$$\epsilon_2 = \frac{\sigma_{x_2}'}{E_2} + \alpha_2\Delta t, \tag{10}$$

where α_1 and α_2 – thermal expansion coefficients of bimetal layers; σ_{x_1}' and σ_{x_2}' denote stress in the upper and bottom layers and do not depend on y.

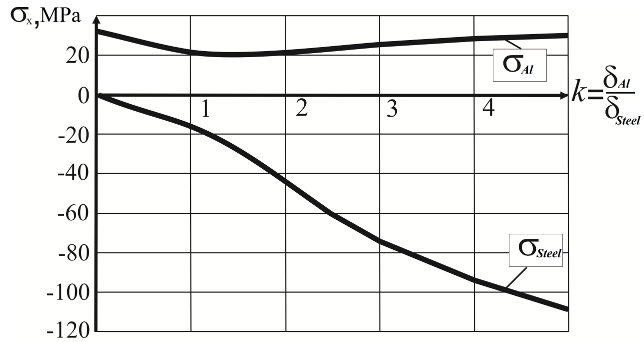


Figure 2: Thermal stress calculated using (15) and (16) on the internal boundary of AA1135/Steel composite during its cooling

If the right part of (9) is equal to the right part of (10), then:

$$\frac{\sigma_{x_1}'}{E_1} + \alpha_1\Delta t = \frac{\sigma_{x_2}'}{E_2} + \alpha_2\Delta t. \tag{11}$$

while the axis load:

$$N = \sigma_{x_1}'\delta_1 + \sigma_{x_2}'\delta_2 = 0. \tag{12}$$

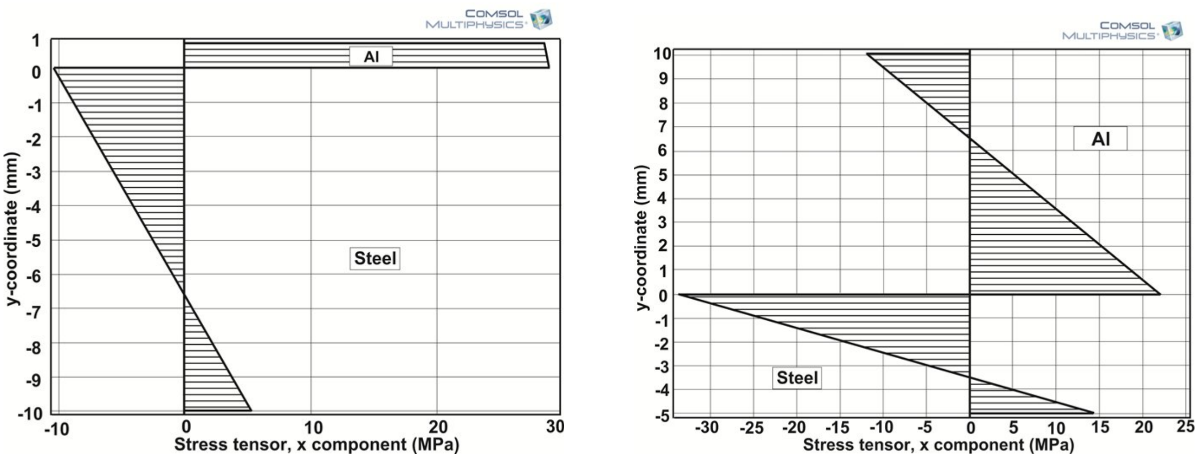
The solution set of system of equations with (11) and (12) presents the expression for calculating stress values:

$$\sigma_{x_1}' = -\frac{(\alpha_1 - \alpha_2)\,\Delta t}{\left(\dfrac{1}{E_1\delta_1} + \dfrac{1}{E_2\delta_2}\right)}, \quad \sigma_{x_2}' = \frac{(\alpha_1 - \alpha_2)\,\Delta t}{\left(\dfrac{1}{E_1\delta_1} + \dfrac{1}{E_2\delta_2}\right)}. \tag{13}$$

The sum of σ_{x_1}' and σ_{x_2}' across the layer thicknesses represents the bending moment with $\frac{\delta_1+\delta_2}{2}$ length displacement vector:

$$M_x' = \frac{(\alpha_1 - \alpha_2)\,\Delta t\,(\delta_1 + \delta_2)}{\left(\dfrac{1}{E_1\delta_1} + \dfrac{1}{E_2\delta_2}\right)2}. \tag{14}$$

To calculate thermal stress in the cooled bimetallic element with the change in temperature Δt and undergoing bending moment $\overrightarrow{M_x'}$, the bending moment of the opposite to $\overrightarrow{M_x'}$ direction and equal to $|\overrightarrow{M_x'}|$ should be applied to the considered element. Thus $\overrightarrow{M_x'}$ and $-\overrightarrow{M_x'}$ cancel each other and only the contribution of cooling can be assessed. The thermal stress values of Al/steel bimetal considering (8), (13) and (14) can be calculated using:



(a) (b)

Figure 3: Thermal stress distribution of AA1135/Steel composite during its cooling obtained using COMSOL: $k = 0,07$ (a) and $k = 2$ (b)

$$\sigma^t_{x_{Al}} = -\frac{(\alpha_1 - \alpha_2)\,\Delta t}{\left(\dfrac{1}{E_1\delta_1} + \dfrac{1}{E_2\delta_2}\right)} \times \left[\frac{1}{\delta_1} + \frac{(\delta_1+\delta_2)\,E_1 y}{2\,(E_1J_1 + E_2J_2)}\right], \tag{15}$$

$$\sigma^t_{x_{steel}} = \frac{(\alpha_1 - \alpha_2)\,\Delta t}{\left(\dfrac{1}{E_1\delta_1} + \dfrac{1}{E_2\delta_2}\right)} \times \left[\frac{1}{\delta_2} + \frac{(\delta_1+\delta_2)\,E_2 y}{2\,(E_1J_1 + E_2J_2)}\right], \tag{16}$$

According to the calculation results (fig. 2) maximum stress occurs in the AA1135 layer when AA1135 to steel thickness ratio is below 0.1 and higher than 4 $k < 0.1$ and $k > 4$. However the maximum stress values are lower than AA1135 layer yield stress.

To verify the obtained results the cooling of the composite was simulated using FEM software COMSOL Multiphysics. Linear elastic material model with plane stress 2D approximation was applied to carry out simulation. The geometry of the was meshed with rectangular.

The bimetal plate was cooled from initial $T_{ref} = 600\,^{\circ}\mathrm{C}$ to room temperature. The process of cooling was considered stationary because during experimental studies the specimen were slowly cooled in furnace. The boundary conditions for the model included one fixed constraint point and one point with displacement in y-direction prescribed to be zero. The bimetal plate was assumed to have no initial stresses and strains before cooling. The materials of the model were assumed to be isotropic. The calculated results for $k = 0.07$ and $k = 2$ are presented on fig. 3.

The comparison between FEM simulation and calculated using equations (15) and (16) results revealed the convergence in the stress values near the bond area.

FEM simulation allowed to consider the impact of thin interlayers of Ni and intermetallics on the stress-strain state. FEM simulation results for various k values are presented on fig. 4. The thickness values of Ni and diffusion zone were both 50 μm. The interlayers were simulated as individual parts of the model and were meshed.

The FEM simulation results reveal tensile stresses in the intermetallic layer to exceed the yield point of $NiAl_3$ [12], when $k = 0.07$ and $k = 5$, which apparently leads to the rupture.

The comparison between calculated in this study results and the experimental results obtained in [13] reveals thermal stress value to reach 87 MPa when $k = 0.07$, which is sufficient for rupture of the composite due to breakdown of $NiAl_3$. When $k = 2$ thermal stress value reaches 24 MPa in the whole range of intermetallic interlayer thickness values (up to 250 μm) and no rupture was observed (fig. 5).

4 Conclusion

- Heat treatment of the 12X11VMF+Np2+AA1135 composite leads to the formation of the intermetallic interlayer between Np2 and AA1135. The interlayer is composed of two zones: adjacent to AA1135 $NiAl_3$ zone and adjacent to Ni Ni_2Al_3 zone. When the thickness of the intermetallic layer is higher than 30 μm, the breakdown of $NiAl_3$ is observed during

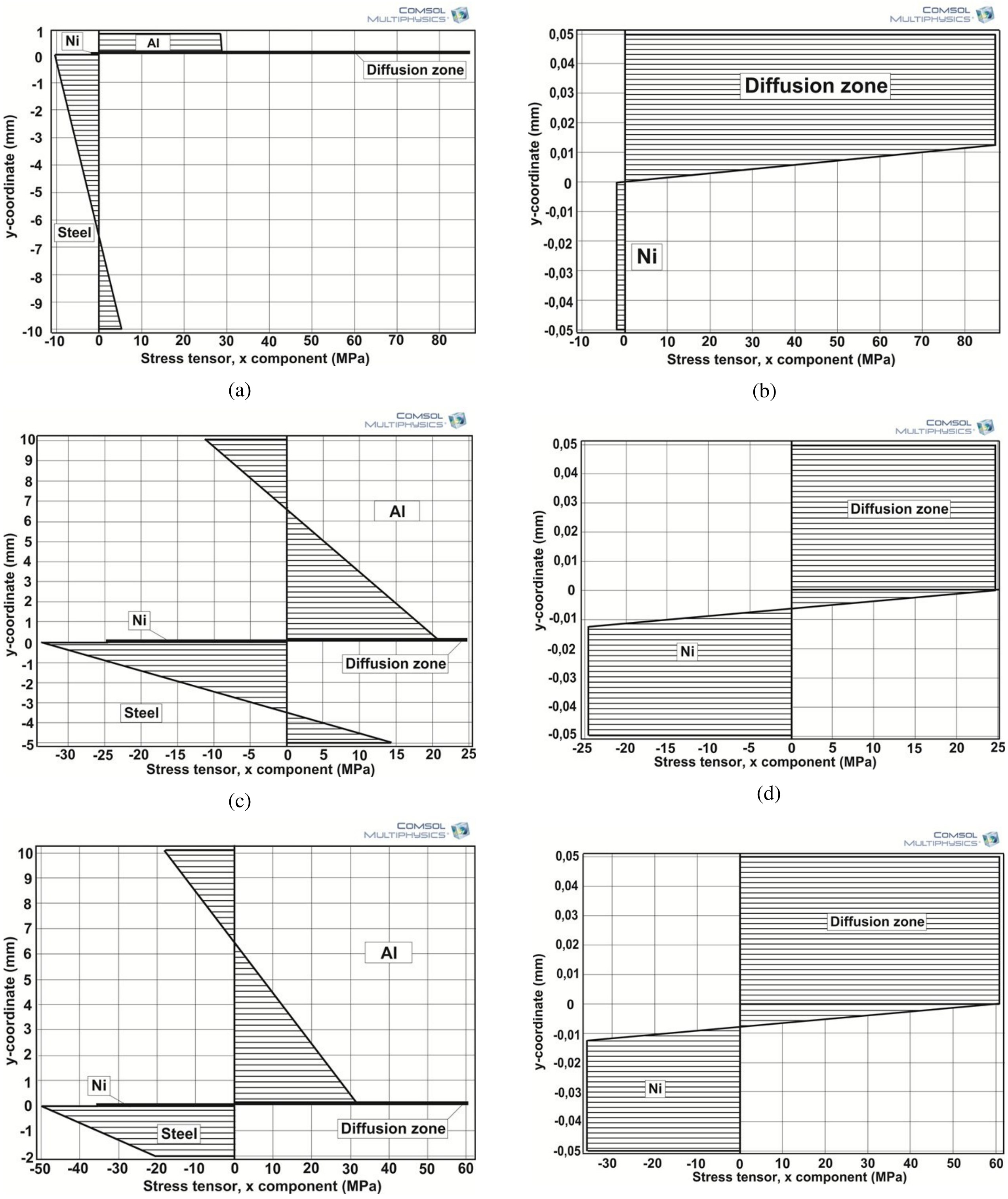
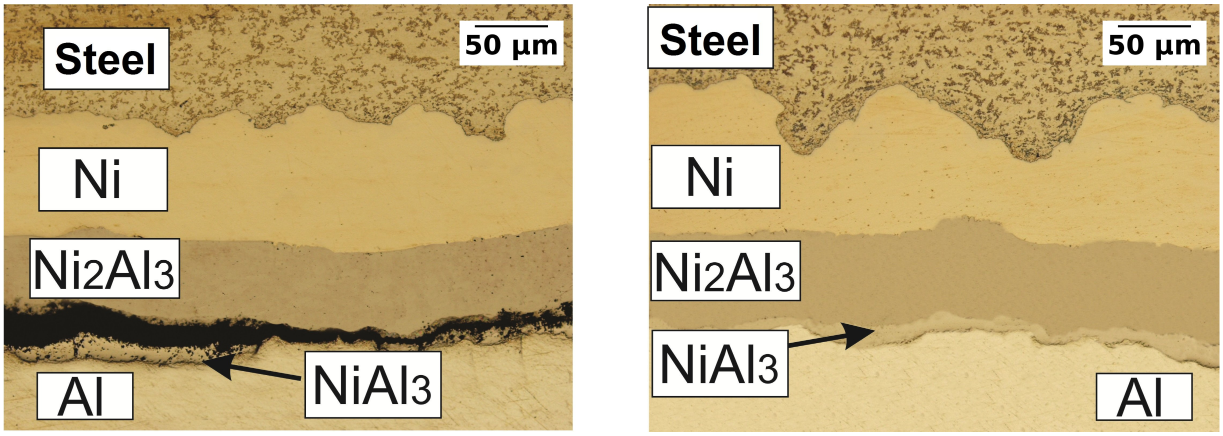


Figure 4: Thermal stress distribution for the composite (a, c, e) through thin interlayers (b, c, f) after cooling from 600 °C 12X11VMF+Np2+AA1135 composite $k = 0,07$ (a, b), 2 (c, d), 5 (e, f)



(a) (b)

Figure 5: 12X11VMF+Np2+AA1135 microstructure after cooling from 600 °C (heat treatment took 5 hr.), diffusion zone was formed, $k = 0,07$ (a) and $k = 2$ (b)

the process of cooling of the composite which leads to the separation of AA1135 layer. The separation is observed only for 12X11VMF to AA1135 thickness ration $k < 0.1$ and $k > 4$. $NiAl_3$ rupture is caused by thermal stress which exceeds the yield point of the intermetallic. Ni/Ni_2Al_3 coating is formed on the surface of steel plate.

- The calculated values of thermal stress can be feasibly used to develop technological process of the laminated Ni/Ni_2Al_3 coating manufacture namely to choose the appropriate EW, pressure treatment and heat treatment parameters.

5 Acknowledgements

The present study was carried out according to the assignment of Russian Ministry of Education No 11.1865.2014/K.

References:

[1] S.C. Deevi et al. "Reactive spraying of nickel-aluminide coatings". *Journal of thermal spray technology* 6.3 (1997), pp. 335–344.

[2] M.H. Enayati et al. "Nanocrystalline NiAl Coating Prepared by HVOF Thermal Spraying". *Journal of thermal spray technology* 20.3 (2011), pp. 440–446.

[3] Yuquan Ding et al. "PVD NiAl intermetallic coatings: microstructure and mechanical properties". *Surface and Coatings Technology* 94 (1997), pp. 483–489.

[4] O Culha et al. "Microstructural, thermal and mechanical properties of HVOF sprayed Ni–Al-based bond coatings on stainless steel substrate". *Journal of Materials Processing Technology* 204.1 (2008), pp. 221–230.

[5] V. Zadorozhnyy et al. "Coating of metals with intermetallics by mechanical alloying". *Journal of Alloys and Compounds* 509 (2011), S507–S509.

[6] Chia-Che Wu and Fan-Bean Wu. "Microstructure and mechanical properties of magnetron co-sputtered Ni–Al coatings". *Surface and Coatings Technology* 204.6 (2009), pp. 854–859.

[7] Donald F Susan and A.R Marder. "Ni–Al composite coatings: diffusion analysis and coating lifetime estimation". *Acta materialia* 49.7 (2001), pp. 1153–1163.

[8] Z.D. Xiang et al. "A phenomenological model for lifetime design of Ni_2Al_3/Ni hybrid coating formed on creep resistant ferritic steels". *Journal of Materials Science* 47.1 (2012), pp. 257–266.

[9] Z.D. Xiang et al. "Degradation kinetics at 650 °C and lifetime prediction of Ni_2Al_3/Ni hybrid coating for protection against high temperature oxidation of creep resistant ferritic steels". *Corrosion Science* 53.10 (2011), pp. 3426–3434.

[10] Z.D. Xiang et al. "Steam oxidation resistance of Ni-aluminide/Fe-aluminide duplex coatings formed on creep resistant ferritic steels by low temperature pack cementation process". *Corrosion Science* 53.1 (2011), pp. 496–502.

[11] V.G. Shmorgun et al. "The kinetics of diffusion processes in the nickel-aluminum composition". *Russian Journal of Non-Ferrous Metals* 50.3 (2009), pp. 286–289.

[12] GK Dey. "Physical metallurgy of nickel aluminides". *Sadhana* 28.1-2 (2003), pp. 247–262.

[13] V.G. Shmorgun, A.I. Bogdanov, and Yu.P. Trykov. "Otsenka termicheskikh napryazheniy v svarennom vzryvom sloistom kompozite stal' + nikel' + alyuminiy posle termoobrabotki". *Deformation and Fracture of Materials* 9 (2013), pp. 43–46.