EVALUATION OF MECHANICAL PROPERTIES OF NICKEL- PHOSPHORUS LAYER/ALUMINUM ALLOY SANDWICH-STRUCTURE

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Abstract

Due to the reduction in production costs, not only in the automotive industry, more and more sandwich-structure parts are emerging to replace expensive, technologically complex elements such as cooling rotors in electrical installations. They are required to meet a complex set of attributes - resistance to abrasive wear, anti-corrosion requirements, and especially manufacturing costs.

This article discusses and compares the mechanical properties of a critical part (cooling rotor) made as a sandwich structure of aluminum alloys and nickel-phosphorus (NiP) coatings.

The specific mechanical and corrosive properties of the thin NiP film vary with the percentage of phosphorus and the heat treatment. On the other hand there is the loss of mechanical properties of aluminum alloy at the temperatures of the nickel-phosphorus cure.

The aim of this article is to find the appropriate mechanical properties of this sandwich-structure part in the view of changing mechanical properties of each of the sandwich components. To obtain these properties, indentation methods and finite element methods are used.

Keywords: Indentation methods, nickel-phosphorus layer, aluminum alloy, mechanical properties, finite element methods

1. INTRODUCTION

Reduction of manufacturing costs should be a part of every modern production. In most cases this leads to increased competitiveness and better place on market. One of the possible solutions to achieve this is the use of sandwich-structure parts. These sandwich-structures can be used instead of expensive and technologically complex manufacturing operations. There are usually high requirements, in terms of abrasive resistance, corrosion resistance and cost, on such sandwich-structure parts. Another aim could be obtaining of better mechanical properties.

This article discuses and compares mechanical properties of critical part - cooling rotor - made as sandwich-structure part of aluminum alloy and nickel-phosphorus coating - abbreviated NiP.

Specific mechanical and corrosive properties of NiP coating depends on the relative amount of phosphorus and on heat treatment. The adverse effect is decrease of mechanical properties of aluminum alloys at temperatures of NiP coating heat treatment.

The goal of this article is to find the appropriate mechanical properties of the whole sandwich-structure part in the view of changing mechanical properties of each of the sandwich components. To obtain these properties, indentation methods and finite element methods are used.

2. CHOICE OF MATERIAL AND SURFACE TREATMENT

There is a requirement of as high as possible mechanical properties of the critical part as well as the requirement of corrosion resistance of 400 hours in ISO EN 9227 test. The finished part (on **Figure 1**) has more than 100 openings (1 mm in diameter) along its circumference which greatly reduces its overall strength. Due to complex machining of the part and also due to pricing policy the AW-Al Si1MgMn-T6 alloy was chosen as a base material. The required thickness of surface layer is 25 µm. The usual hard anodized coating was impossible to use because of its physical limits, mainly the lack of layer growth on sharp edges. Other adverse effects were the thinner layer inside the openings and the porosity of this layer - visible on **Figure 2**. All mentioned effects lead to failure to meet the corrosion resistance requirements.

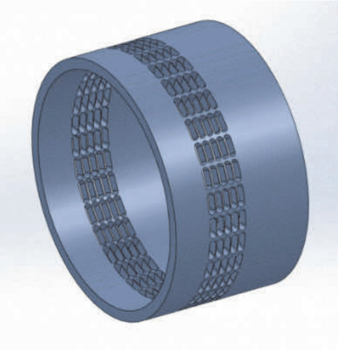

Figure 1 Critical part - cooling rotor

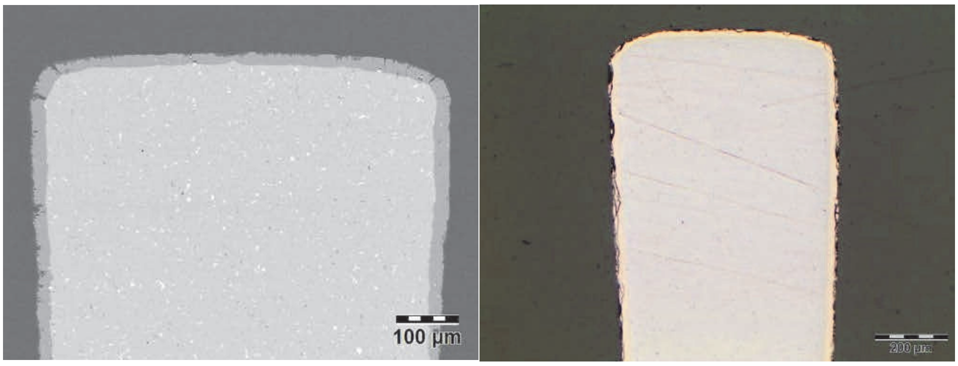

Figure 2 Hard anodized coating (better sample on left, worse on right)

Due to reasons mentioned above the electrochemically produced NiP coating was chosen. For comparison with hard anodized coating there is NiP coating on **Figure 3**. The higher is the relative amount of phosphorus in this coating, the higher is its corrosion resistance but on the other hand the lower is its surface hardness. It is possible to improve the surface hardness by heat treatment, but the temperature of such a treatment is in range of temperatures that lead to thermal degradation of the base aluminum alloy. This could be seen from **Figure 4** and **Figure 5**.

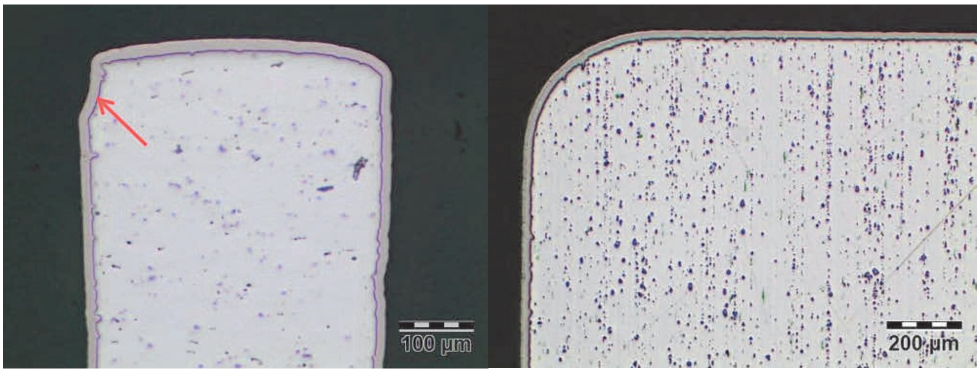

Figure 3 NiP coating

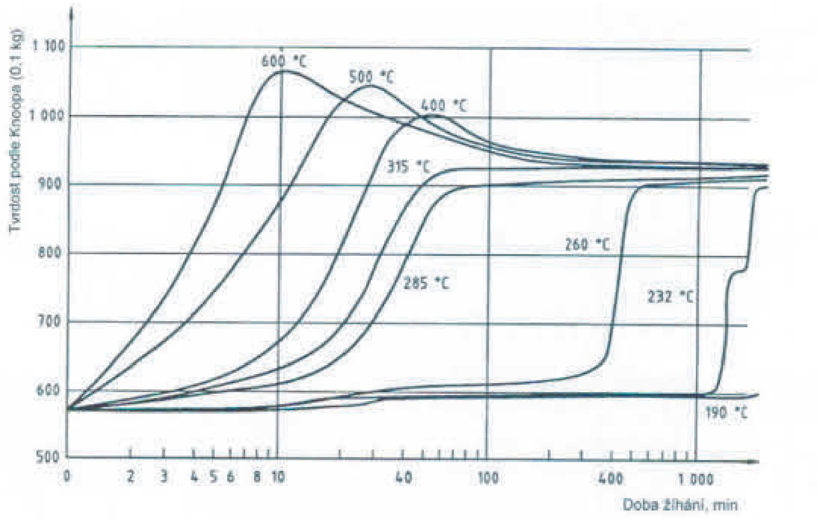

Figure 4 Hardening of NiP coating [1]

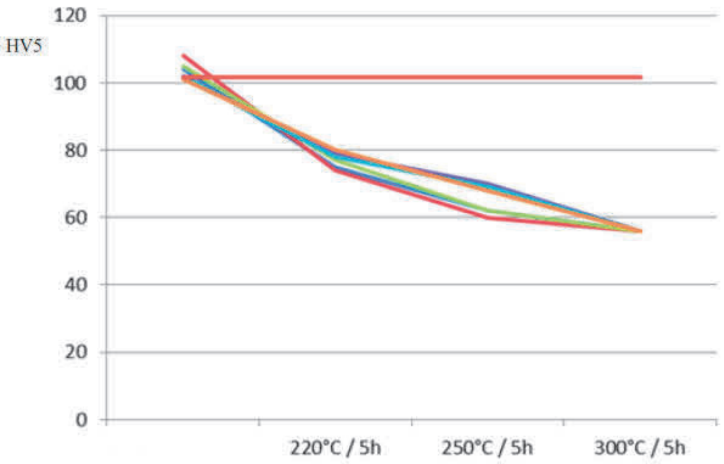

Figure 5 Aluminum alloy thermal hardness loss [1]

3. EXPERIMENTAL RESULTS

To obtain values of mechanical properties, methods and equations described in [2] and [3] were used. The measurement was done on samples with same chemical composition of NiP layer but with different heat treatment. Results of these measurements are presented in **Table 1** and **Table 2**.

Table 1 Hardness of base material and surface layer with type 1 heat treatment

Sample	Al-alloy after heat treatment (HV5)	NiP before heat treatment (HV0.1)
1.	108	460
2.	105	445
3.	106	460
4.	101	465
5.	105	455
Average	105	457

Table 2 Hardness of base material and surface layer with type 2 heat treatment

Sample	Al-alloy before heat treatment (HV5)	NiP after heat treatment (HV0.1)
1.	58	890
2.	60	900
3.	56	910
4.	58	905
5.	58	910
Average	58	903

4. FEM MODEL

It is impossible to obtain a stress/strain function from one single indentation measurement with constant force as it is possible from tensile strength test. Similarly the hardness value is not enough to characterize mechanical properties of material for elastic-plastic FEM analysis. However based on [4] and [5] we can expect yield strength $\sigma_Y = H/C$ with *C* being approximately 3 and *H* being hardness value in MPa. The mean value of contact pressure is equal to hardness *H*, while hardness itself is $H = HV/0.0945$. The aim of our model is to show the influence of (varying) yield strength of aluminum alloy to local toughness of NiP coated sample.

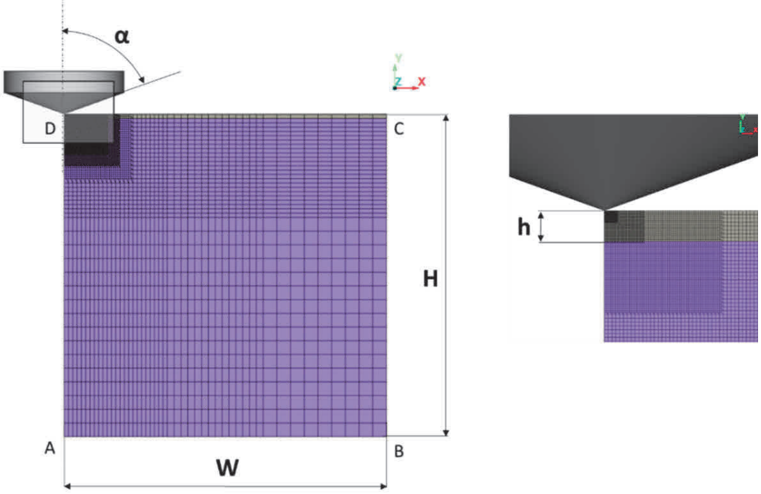

Figure 6 FEM Axisymmetrical model

For the purpose of analysis it is possible to substitute Vickers indenter with conical one. If this conical indenter have the angle α = 70.3°, then for given depth of indentation it gives exactly the same indentation area as original Vickers indenter. This lets us make a simplified 2D axisymmetrical model. This model in our case is made for ABAQUS 6.14 solver and consists of three- and four-node elements (called CAX). The indenter is simulated by totally rigid analytical surface. In **Figure 6** there are marked boundaries with defined boundary conditions. On D-A boundary it is the condition of symmetry. On A-B it is zero movement in *Y* axle direction. The dimensions are width $W = 1.5$ mm, height $H = 1.5$ mm and surface layer thickness $h = 20$ μm. Loading is controlled by forced movement of indenter $u_y = 5$ μm. Between the indenter and the surface of sample there is a contact condition with friction coefficient $f = 0.1$. The normal behavior of indenter is based on nonlinear penalty method.

Materials of both base aluminum alloy and NiP coating are defined as bilinear models represented by equations (1) and (2), where σ_Y is yield stress, *E* is Young modulus, ε is elastic strain, ε_{pl} is plastic strain and E_{pl} is plastic modulus. Plastic modulus is expected $E_{pl} = E/10^4$.

$$\sigma = E\varepsilon \qquad \text{for } \sigma \leq \sigma_Y \tag{1}$$

$$\sigma = E_{pl} \cdot \varepsilon_{pl} + \sigma_Y \qquad \text{for } \sigma > \sigma_Y \tag{2}$$

The first model has more rigid base material (σ_{YAl} = 370 MPa for aluminum alloy) and less rigid surface coating (σ_{YNiP} = 1 612 MPa for NiP) representing type 1 heat treatment. The second model represents the type 2 heat treatment with yield strengths σ_{YAl} = 205 MPa and σ_{YNiP} = 3 185 MPa for aluminum alloy and NiP layer respectively. Young's modulus for aluminum alloy is E_{Al} = 70 GPa, for NiP coating we expect E_{NiP} = 210 GPa. Plastic moduli E_{pl} are chosen as 10 % of corresponding yield strength.

5. FEM RESULTS

On **Figure 7** there is von Mises stress for both models, on the right side is model of heat treatment 1, and on the left side is heat treatment 2. For the first variant with more rigid base material and less rigid surface layer there is substantially lower maximal stress, than it is in second variant. Also in the first variant has the maximal stress on border between the two materials while in the second variant the maximum is in the contact with indenter.

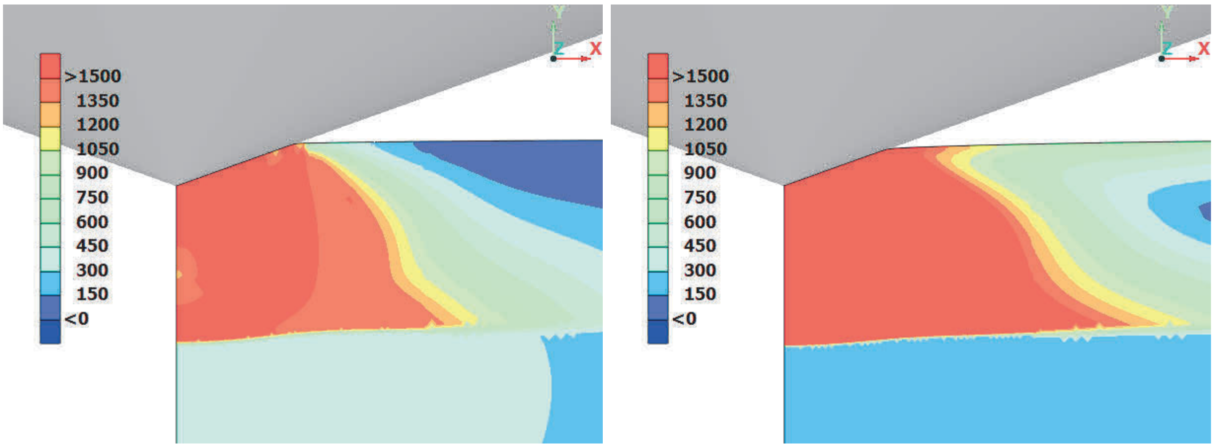

Figure 7 Von Mises stress (MPa) - heat treatment type 1 on left and heat treatment type 2 on right

Also important are the loading curves i.e. force/depth dependence. This is shown on **Figure 8** where the first type of heat treatment is drawn in red and second type in blue.

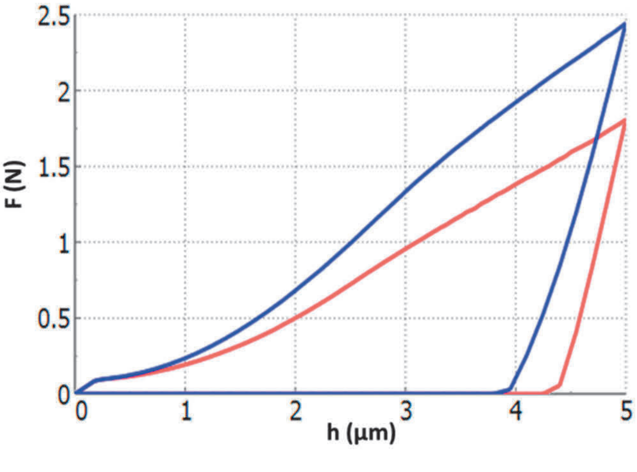

Figure 8 Loading curves. Red for heat treatment type 1, blue for heat treatment type 2

6. CONCLUSION

From the loading curves (**Figure 8**) it is clearly visible, that in case of limited area contact (with depth of penetration up to 5 μm) it is more advantageous to use sample with more rigid behavior on the surface - i.e. heat treatment type 2. On the other hand the heat treatment type 1 would be better for higher global (less centralized) loading because of better mechanical properties of base material. Given the requirements on the critical part - cooling rotor - in this case the better variant is heat treatment type 2, which leads to "very rigid surface layer, softer base material" represented by yield strengths σ_{YAl} = 205 MPa and σ_{YNiP} = 3 185 MPa for aluminum alloy and NiP layer respectively.

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