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INVESTIGATION AND ESTIMATION OF RESIDUAL STRESS IN FLAME SPRAYED AND FUSED NiCrBSi COATINGS

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For thermally sprayed coatings, beside good wear and corrosion resistance there is also a need for a good coating/substrate adhesion, reduced porosity and reduced level of residual stresses. Residual stresses that occur in the substrate/coating system are very significant because their relaxation can cause different coating failures. In this paper, different approaches to investigation of residual stresses in thermally sprayed coatings, have been presented. An analytical model (authors Tsui and Clyne) was used to estimate the distribution of residual stresses in flame sprayed and fused NiCrBSi coatings. These data can be used as input data for the numerical model.

Key words: residual stress, NiCrBSi coatings, flame spraying and fusing

Istraživanje i procjena zaostalih naprezanja u plinski naštrcanim NiCrBSi slojevima. Za toplinski naštrcane slojeve, uz dobru otpornost slojeva na trošenje i koroziju, postoje i zahtjevi za dobrom prionjivosti sloja na podlogu, smanjenom poroznosti i smanjenom razinom zaostalih naprezanja. Zaostala naprezanja koja se pojavljuju u sustavu podloga/naštrcani sloj, osobito su važna, jer se njihovom relaksacijom mogu pojaviti razna oštećenja sloja. U ovome radu prikazani su pristupi istraživanju zaostalih naprezanja u toplinski naštrcanim slojevima, te je na osnovi analitičkog modela (autori Tsui i Clyne) procijenjena raspodjela zaostalih naprezanja za NiCrBSi slojeve nanesene postupkom plinskog naštrcavanja praha s utaljivanjem. Ovi podaci mogu se koristiti kao ulazni podaci za numerički model.

Ključne riječi: zaostala naprezanja, NiCrBSi slojevi, plinsko naštrcavanje s utaljivanjem

INTRODUCTION

Flame spraying, as a type of thermal spraying, is used for repairing damaged and worn elements of tribomechanical systems, and also for protection of new parts from wear and corrosion. Flame spraying and fusing of self-fluxing alloys is a new type of flame spraying, also called hot flame spraying, where metallurgical bond between coating and substrate is created. This procedure is standardized as HRN EN ISO 14920:2002 (in Croatia) and as an international standard it is known as EN ISO 14920:1999 "Spraying and fusing of self-fluxing alloys". Self-fluxing alloys are a complex Ni-Cr-B-Si-Fe-C system. These alloys have high wear and corrosion resistance due to hard phases (carbides, borides, silicides).

Due to high fusing temperatures, as well as differences in temperature, sudden changes in structure and volume can occur, and developed residual stresses can have negative influence on coating characteristics.

Residual stresses are usually classified as residual stresses developed during the process, due to cool-down and contraction of particles and residual stresses due to different thermal expansion coefficients of coating and substrate material.

During spraying procedure, molten particles of the coating material hit the substrate surface, flatten and cool down in a short period of time. Thermal contraction of molten particles is limited by the substrate or by a previous layer of deposition, so the tensile stresses occur in the coating. Kuroda and Clyne [1] call it quenching stress – stress due to cool-down and contraction of particles. Sometimes these residual stresses can cause spontaneous debonding during cool-down period or during service by external loading.

Beside term quenching stress, different terms are used for this type of stress: deposition stress, primary stress, intrinsic stress, growth stress. Maximum possible residual stress in the particle, is [1]:

$$\sigma_q = \frac{E_d \alpha_d \Delta T}{1 - \nu_d} \qquad (1)$$

The second type of residual stress, so called cooling stress, occurs when the spraying procedure is finished and the substrate and coating are cooling down from the deposition temperature to room temperature. There are other terms used for this type of stress: secondary stress,

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secondary cooling stress, differential thermal contraction stress, thermal stress. These stresses occur because of the difference in thermal contraction of substrate and coating material, so they are often called thermal expansion coefficient mis-match or CTE mis-match stresses. These stresses are thermal residual stresses of the first order [2]. They can be compressive or tensile. Magnitude of this type of stress depends on temperature, on thermal expansion coefficient of substrate and coating material, and on modulus of elasticity (expression 2).

$$\sigma_d(T_0) = (\alpha_d - \alpha_s)(T_d - T_0)E_d(T_0) \qquad (2)$$

By relaxation of these residual stresses, some cracking in the coating and on the substrate/coating interface can occur, as well as some spallation.

Different laboratory methods were used for testing residual stresses in thermally sprayed coatings. The authors [3-6] used X-ray diffraction method. This is a non-destructive method, based on the fact that when there is stress present, in materials with crystal structure, there is a change in spacing between the crystal planes within crystal lattices [7]. This method has a slight disadvantage, i.e. X-rays cannot penetrate deep into the coating, so it can be used only to analyse stress in the surface layer of coating. Neutrons can penetrate the material easier, so the neutron diffraction method was also used [8-10]. With the layer removal method [11-13] and the hole drilling method [14-16] changes in micro-strain of the surface are being monitored, while thin layers of coating are being removed. While bending the substrate/coating system [1, 3, 17-20] the curvature method uses measurements of curvature change to estimate quenching stresses. This method is additionally improved by non-contact measurements of curvature by video recording [17]. Apart from these experimental researches there are numerous analytical and numerical models as well [1, 15, 18, 19, 21].

DESCRIPTION OF AN ANALYTICAL MODEL FOR ESTIMATION OF RESIDUAL STRESSES

Tsui and Clyne [18] have developed a model for distribution of residual stresses in the substrate/coating system. Figure 1 shows the influence of residual stresses

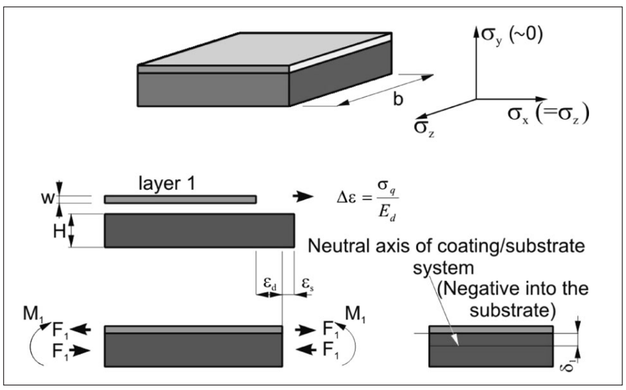

Figure 1. Generation of the bending moment during spraying of the first layer [18]

due to cooling and contraction of particles (quenching stress) on the substrate/coating system (the first layer is shown). The strain of the applied coating ε_d and the substrate ε_s are caused by a pair of same but opposite forces F_1. The force in the coating is tensile, and the force in the substrate is compressive. This pair of forces causes the bending moment M_1.

The expressions for quenching stress, for the lower and upper surface of the *substrate,* after the deposition of *n* layers*,* are as follows:

$$\sigma_{sbn} = \sigma_{s|y=-H} = \sum_{i=1}^{n}\left(\frac{-E_sF_i}{b(HE_s + (i-1)wE_d} + E_s(\kappa_i - \kappa_{i-1})(H+\delta_i)\right) \qquad (3)$$

$$\sigma_{snt} = \sigma_{s|y=0} = \sum_{i=1}^{n}\left(\frac{-E_sF_i}{b(HE_s + (i-1)wE_d} + E_s(\kappa_i - \kappa_{i-1})\delta_i\right) \qquad (4)$$

The expression for this type of stress in the *coating* at the midpoint of the *jth* layer (1≤ *j* ≤ *n*) is as follows:

$$\sigma_{dj} = \sigma_{d|y=\left(j-\frac{1}{2}\right)w} = \frac{F_j}{bw} - E_d(\kappa_j - \kappa_{j-1})\left(\left(j-\frac{1}{2}\right)w - \delta_j\right) + \sum_{i=j+1}^{n}\left(\frac{-E_dF_i}{b(HE_s + (i-1)wE_d} - E_d(\kappa_i - \kappa_{i-1})\left(\left(j-\frac{1}{2}\right)w - \delta_i\right)\right) \qquad (5)$$

Tsui and Clyne [18] have also developed additional expressions to describe the second type of stress (cooling stress). Figure 2 shows the influence of this type of stress on the substrate/coating system.

The expressions for this type of stress for lower and upper surface of the *substrate* are as follows:

$$\sigma_{s|y=-H} = \frac{-F_{(CTE)}}{bH} + E_s(\kappa_c + \kappa_n)(H+\delta) \qquad (6)$$

$$\sigma_{s|y=0} = \frac{-F_{(CTE)}}{bH} + E_s(\kappa_c + \kappa_n)\delta \qquad (7)$$

Cooling stresses that occur in the *coating* can be calculated from the following:

$$\sigma_{d|y=h} = \frac{F_{(CTE)}}{bH} + E_d(\kappa_c + \kappa_n)(h-\delta) \qquad (8)$$

$$\sigma_{d|y=0} = \frac{F_{(CTE)}}{bH} + E_d(\kappa_c + \kappa_n)\delta \qquad (9)$$

Force $F_{(CTE)}$ [N], curvature change $\kappa_c - \kappa_n$ [1/mm] and the distance from the neutral axis to the interface of the substrate/coating system, δ [mm], are calculated by:

$$F_{CTE} = \frac{2(\kappa_c - \kappa_n)\Sigma_c}{h+H} \qquad (10)$$

$$\kappa_c - \kappa_n = \frac{6E_dE_shH(h+H)\Delta\varepsilon}{E_d^2h^4 + 4E_dE_sh^3H + 6E_dE_sh^2H^2 + 4E_dE_shH^3 + E_s^2H^4} \qquad (11)$$

$$\delta = \frac{E_dh^2 - E_sH^2}{2(E_dh + E_sH)} \qquad (12)$$

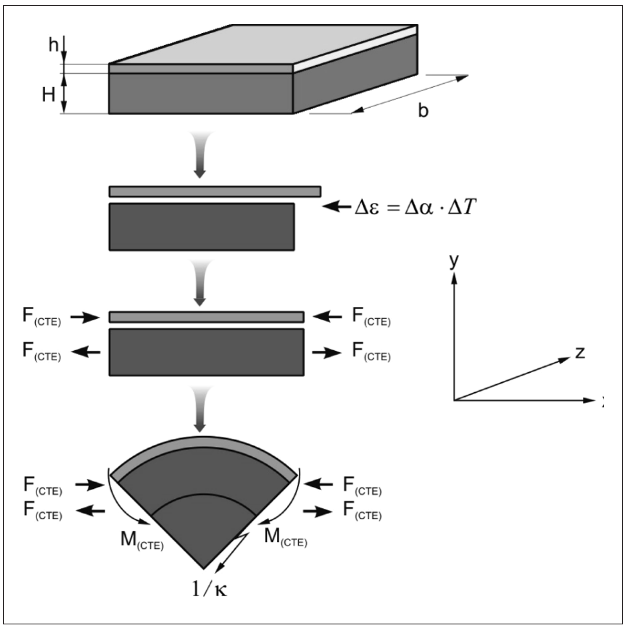

Figure 2. Cooling stress in the substrate/coating system [18]

The stiffness of the substrate/coating system, can be calculated by using:

$$\Sigma_c = bhE_d\left(\frac{h^2}{3} - h\delta + \delta^2\right) + bHE_s\left(\frac{H^2}{3} + H\delta + \delta^2\right) \quad (13)$$

In order to calculate the curvature change of the substrate/coating system, strain $\Delta\varepsilon$ is needed:

$$\Delta\varepsilon = (\alpha_d - \alpha_s)(T_d - T_0) \quad (14)$$

CALCULATION OF RESIDUAL STRESSES IN FLAME SPRAYED COATINGS

The main purpose of estimating residual stresses by using previously mentioned and described analytical model [18] is to use these data as the input data for numerical modeling of the substrate/coating system in order to determine cracking resistance of coatings. Numerical model can be used to estimate data for deflection in the direction of the load and equivalent stresses (von Mises) and it can be compared to experimental researches of cracking (fracture) resistance of coatings under the influence of bending load [22].

Table 1 [22], shows which control factors of cracking resistance were used, for Taguchi experimental design.

Table 1. **Levels of control factors of fracture resistance**

Control Factors	Level 1	Level 2	Level 3
Substrate Material	M1 (C45)	M2 (42CrMo4)	M3 (X6CrNiMo18-10-2)
Type of Coating	P1 (NiCrBSi)	P2 (NiCrBSi+WC)	P3 (NiCrWBSi)
Coating Thickness	D1 (0,3 mm)	D2 (0,5 mm)	D3 (0,8 mm)

Substrate materials (steels) are signed according to their chemical composition, by EN 10027 standard. Table 2 shows Taguchi orthogonal experimental design [23-25].

Table 2. **Taguchi L_9 (3^3) orthogonal experimental design**

Number of experiment	Substrate Material	Type of Coating	Coating Thickness
1	M1	P1	D1
2	M1	P2	D2
3	M1	P3	D3
4	M2	P1	D2
5	M2	P2	D3
6	M2	P3	D1
7	M3	P1	D3
8	M3	P2	D1
9	M3	P3	D2

Orthogonal arrays are special sets of Latin squares, and they were designed by Taguchi as a basis for experimental design. Three samples were used for each experiment, so the total number of samples was 27.

From the definition of quenching stress, it is possible to conclude that for flame sprayed and simultaneously fused coatings, due to high fusion temperature (1000°C), stresses that occur during cooling and contraction of particles during flame spraying, can be disregarded. Fusing temperature is high enough to remove stresses by annealing [10]. Only cooling stresses that occur after fusing can be of any importance. Since cooling after fusing occurs very slowly and the coating materials and the substrate have similar elasticity characteristics (elasticity modulus) and thermal characteristics (thermal expansion coefficient), the level of residual stresses mostly influenced by a huge difference between the fusing temperature and room temperature can be predicted.

Previously described model [18] was used to calculate the level of residual stresses. Data on thermal and mechanical characteristics of coatings and substrates are given in the following part of the paper.

Thermal expansion coefficients of NiCrBSi alloys are as follows [26-28]: $\alpha_{0\text{-}100°C} = 11{,}4 \cdot 10^{-6}$ K^{-1}, $\alpha_{0\text{-}300°C} = 12{,}8 \cdot 10^{-6}$ K^{-1}, $\alpha_{0\text{-}700°C} = 13{,}4 \cdot 10^{-6}$ K^{-1}, $\alpha_{0\text{-}900°C} = 15{,}4 \cdot 10^{-6}$ K^{-1}. These data cannot be considered as valid for NiCrBSi+WC composite coating since the existence of coarse WC particles affects these results. As a result, there are no estimates of residual stresses for these samples. Thermal expansion coefficients for substrate materials are as follows [29] (for temperatures from 20°C to 900°C): $\alpha_{C45} = 14{,}7 \cdot 10^{-6}$ K^{-1}, $\alpha_{42CrMo4} = 15{,}2 \cdot 10^{-6}$ K^{-1} and $\alpha_{X6CrNiMo18\text{-}10\text{-}2} = 18 \cdot 10^{-6}$ K^{-1}. Data on elasticity modulus for NiCrBSi alloys were acquired from the manufacturer [27]. It is 200 GPa. By using these data and expressions (6) to (14) residual stresses in the coatings can be calculated (Table 3), for the cross section of sample

Table 3. **The results of calculation (using MS Excel) of residual stresses in the substrate/coating system**

Sample designation (according to Table 2)	Cooling stresses			
	$\sigma_{d\|y=h}$ [MPa]	$\sigma_{d\|y=0}$ [MPa]	$\sigma_{s\|y=0}$ [MPa]	$\sigma_{s\|y=-H}$ [MPa]
M1P1D1	124	124,5	-13,3	6,8
M1P3D3	102,9	106,3	-32,4	17
M2P1D2	32,9	33,3	-6,1	3,2
M2P3D1	35,4	35,6	-3,8	1,9
M3P1D3	-382,2	-395	120,3	-63,3
M3P3D2	-428,6	-433,8	79,6	-41

(*b*=25 mm; *h*=0,3 to 0,8 mm; *H*=11,4 to 10,9; *H*+*h*=const =11,7 mm).

Figure 3 shows the distribution of stress for M1P1D1 sample combination (substrate material is C45 steel, coating material is NiCrBSi, coating thickness is 0,3 mm).

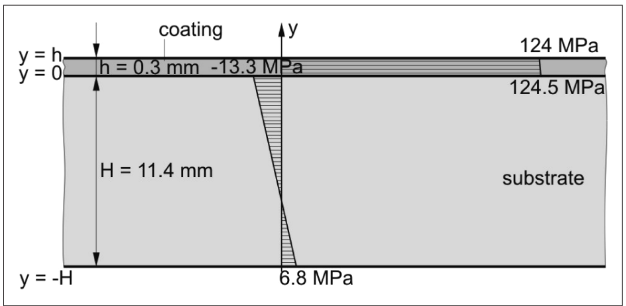

Figure 3. Stress distribution for M1P1D1 sample

CONCLUSION

The residual stresses were calculated for the state after the flame spraying procedure. Since the residual stresses for samples made from stainless steel (M3P1D3 and M3P3D2) were the highest, so after the fusing and cooling, these samples should also have (according to calculations) the biggest warpage. However, the real situation was just the opposite. The samples with the substrate made from M1 (C45 steel) and M2 (42CrMo4 steel) had the biggest warpage. The reason for this could be that the thermal conductivity coefficient λ (W/mK) was not part of the calculations. Stainless steel has lower thermal conductivity coefficient (≈15W/mK) than carbon steel (≈50 W/mK) and low alloyed steel (≈43 W/mK), because of its high content of alloy elements. It does not conduct heat so well, it cools slower, and the level of residual stresses could be smaller than calculated. The second and more plausible reason is that the residual stresses relaxed after some fractures in the coating appeared when the spraying and cooling procedure were finished. This was proven by metallographic analysis in [22].

Data on distribution of stresses acquired by this analytical model can be used as input data for numerical modeling of the substrate/coating system by finite element method. In finite element software package, with the model (mesh) of finite elements that are interconnected by nodes, defined in pre-processor together with properties of the substrate and the coating material, by sample geometry, load and boundary conditions, it is also possible to define previously estimated distribution of residual stresses in the substrate and the coating.

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List of symbols

σ_q - quenching stress /MPa
E_d - elasticity modulus of coating /MPa
ν_d - Poisson's ratio of coating /-
CTE - coefficient of thermal expansion
α_d - CTE of coating /K^{-1}
ΔT - difference between temperatures of molten and cooled-down coating particles /K
$\sigma_d(T_0)$ - cooling stress /MPa
αs - CTE of substrate /K^{-1}
T_d - substrate/coating interface temperature after spraying /K
T_0 - room temperature /K
E_s - elasticity modulus of substrate /MPa
σ_{sbn} - quenching stress, for lower surface of substrate /MPa
σ_{stn} - quenching stress, for upper surface of substrate /MPa
F_i - force due to cool-down and contraction of particles (for *ith* layer) /N
b - substrate width /mm
H - substrate height /mm
n - number of layers /-
i - layer number, i = 1, …, n
w - layer thickness /mm
$\kappa i - \kappa_{i-1}$ - curvature change for the substrate/coating system, between the deposition of two layers, 1/mm
δ_i - distance from the neutral axis to the interface of the substrate/coating system /mm
σ_{dj} - quenching stress at the midpoint of the *jth* layer of coating /MPa
$\sigma_{s|y=-H}$ - cooling stress, for lower surface of substrate /MPa
$\sigma_{s|y=0}$ - cooling stress, for upper surface of substrate /MPa
$F_{(CTE)}$ - force due to difference between CTE of substrate and CTE of coating /N
$M_{(CTE)}$ - bending moment due to difference between CTE of substrate and CTE of coating /Nmm
$\kappa_c - \kappa_n$ - curvature change for the substrate/coating system /1/mm
$\sigma_{d|y=h}$ - cooling stress, for upper surface of coating /MPa
$\sigma_{d|y=0}$ - cooling stress, for lower surface of coating /MPa
h - coating thickness /mm
$\Sigma\varepsilon$ - stiffness /Nmm^2
$\Delta\varepsilon$ - misfit strain /-

Note: Responsible translator: Željka Rosandić, Faculty of Mechanical Engineering in Slavonski Brod University of Osijek, Slavonski Brod, Croatia