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The Influence of Gas-Dynamic Spraying Temperature on Residual Stresses of the Coating

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Abstract. This article examines the effect of working gas temperature during gas-dynamic spraying (GDS) on residual stresses in coatings made of CRO ceramics and NiAlSiCr metal composites. GDS is a promising technology for applying protective and restorative coatings in mechanical engineering, preventing component overheating (the substrate temperature typically does not exceed 100-150 °C). The method involves the solid-phase bonding of powder particles, accelerated to supersonic speeds, with the component surface due to their plastic deformation upon impact. The working gas is typically heated to temperatures between 300°C and 700°C. Experiments were conducted using a DIMET 405 setup on St3 steel samples at three gas stagnation temperature settings: 200°C, 300°C, and 400°C. Residual stresses were measured using an IKN-3M-129 stress concentration meter. It was found that increasing the working gas temperature from 200°C to 400°C sharply reduced compressive residual stresses (to -121.75 MPa for NiAlSiCr and -81.125 MPa for CRO at 200°C), followed by a transition to low tensile stresses (to +3.5 MPa for CRO). This is explained by the fact that higher temperatures increase particle plasticity, facilitating their deformation and adhesion. A spraying temperature of 400°C was found to be optimal for minimizing residual stresses, which is important for ensuring the stability and durability of the coating.

Key words: temperature, residual stress, coating quality, plasticity, powder

Introduction.

Gas-dynamic spraying (GDS) is a promising technology for applying protective coatings to various mechanical engineering components. The method involves forming a surface layer through the impact of high-speed particles of the applied powder material on the surface of the substrate (component) [1].

Unlike traditional thermal spraying methods (e.g., plasma spraying), where the material particles are completely or partially melted before impact, with GDS the powder remains solid or is heated to a temperature significantly below its melting point [2]. The working gas (often nitrogen, helium, or compressed air) is heated to a temperature typically between 300°C and 700°C (with GDS). A metal or composite powder (e.g., copper, aluminum, zinc, nickel, and their alloys) with a particle size of 1 to 50 μm is fed into the heated gas stream. The gas flow passes through a specialized Laval nozzle or similar device, where it expands, reaching supersonic speeds (hundreds of meters per second) [3]. Powder particles are entrained in this flow and also accelerate. Upon impact with the surface of the part, the kinetic energy of the particles is converted into thermal and plastic deformation energy. The particles are deformed and solid-state bonding (adhesion) occurs with the substrate and with each other. The key to forming a dense coating is for the particles to reach a critical deposition velocity (but not erosion velocity) [4].

Gas-dynamic spraying is an effective method for restoring the geometry and functional properties of worn, corroded, or damaged parts, often in aircraft, mechanical engineering, shipbuilding, and electrical engineering [5].

GDS is actively used to repair cracks, chips, abrasions, corrosion damage, and to restore the geometric dimensions of mounting surfaces [6].

GDS is used for [7]:

- restoring worn bearing or sealing surfaces on crankshafts, pump shafts, and electric motor shafts;
- repairing cracks, holes, and damaged threaded holes in cylinder blocks, gearbox housings, and hydraulic equipment;
- applying conductive layers (e.g., copper or aluminum) to restore contacts, busbars, or repair windings.
- it is especially effective for restoring aluminum and magnesium parts, as the low process temperature prevents their warping and structural changes;
- repairing piston rods, cylinders, and plungers in hydraulic and pneumatic equipment.

The key advantages of GDS make it the preferred choice for many restoration tasks [8]:

- the substrate (workpiece) remains virtually unheated (the temperature typically does not exceed 100-150°C). This eliminates thermal deformation (warping), oxidation, structural changes, and burnout of alloying elements in the base material of the part;
- produces a high-quality coating with high density (porosity <1-3%) and uniformity, ensuring good adhesion and cohesion;
- the absence of an open flame, high-temperature plasma, and toxic compounds (no metal evaporation) makes the GDS process safe and environmentally friendly compared to some other thermal spraying methods;
- allows you to apply coatings from a wide range of metals (Al, Cu, Zn, Ni, Sn) and their mixtures on various substrates (metals, ceramics, polymers).

Successful use of GDS for component refurbishment requires consideration of a number of process features related to preparation, the process itself, and finishing.

Quality surface preparation is critical to ensuring high adhesion. The surface must be thoroughly cleaned of oil, dirt, rust, and old coatings. Abrasive blasting (sandblasting, shot blasting) is often used to roughen and activate the surface, which promotes mechanical adhesion [9]. Different abrasives are used depending on the material.

Coating quality and deposition rate directly depend on the precise setting of the machine parameters [10]. Gas (air) temperature affects particle plasticity. It is selected below the melting point of the powder, but high enough to ensure plastic deformation upon impact. Gas/air pressure determines the gas flow velocity and, consequently, the particle velocity. Higher pressures provide higher velocities and allow the deposition of harder materials. Powder consumption, like that of wire in other types of thermal spraying, controls the thickness and uniformity of the applied layer [11].

After spraying, the coating may require mechanical processing to achieve the required dimensions and surface finish. The applied layer is then machined or ground to the required geometric parameters (e.g., restoring the bore diameter) [12]. In some cases, to improve hermeticity or corrosion resistance, the sprayed coating can be impregnated with polymers or sealants.

Varying the temperature of the thermal spraying process significantly influences the kinetics and mechanisms of coating formation, which, in turn, determines these key characteristics [13].

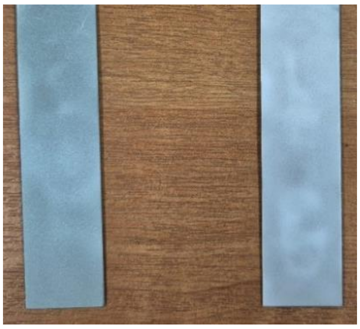
The purpose of this article is to study the effect of spraying temperature on residual stresses in CRO and NiAlSiCr coatings, which will enable the development of process recommendations for producing coatings with improved performance properties.

1. Research methodology

1.1 Materials and equipment

Two spherical powders were used for the experiment: CRO (Metacerampowder 28010, Castolin Eutectic, Ireland) and NiAlSiCr (RotoTecPowder, Castolin Eutectic, Ireland) with a particle size of 10 µm.

The coatings were applied to eight St3 steel samples measuring 100 x 20 x 10 mm for each material (Figure 1a, b).



a) b)

Fig.1. – Samples with gas-dynamic coating: a) CRO; b) NiAlSiCr

Before coating, the samples were degreased. The sample roughness was 3 µm.

Powders were applied using a gas-dynamic method using a DIMET 405 system (Figure 2).

Fig. 2 – DIMET 405 Gas-Dynamic Spraying System
(Russia, Obninsk, Obninsk Powder Spraying Center LLC)

1.3 Experimental modes

For the experiment, temperature modes 2, 3, 4 were used, which indicate the gas deceleration temperature in front of the critical section of the supersonic nozzle:

- mode «2» - 300 °C;
- mode «3» - 400 °C;
- mode «4» - 500 °C.

The constants in the experiment were:

- air pressure P_{air} = 5 MPa;
- powder consumption M_{powder} = 30g/min;
- spraying distance s = 20 mm;
- torch travel speed $V_{traverse}$ = 100 mm/s;
- spray angle φ = 30ºC.

1.4 Determination of residual stresses

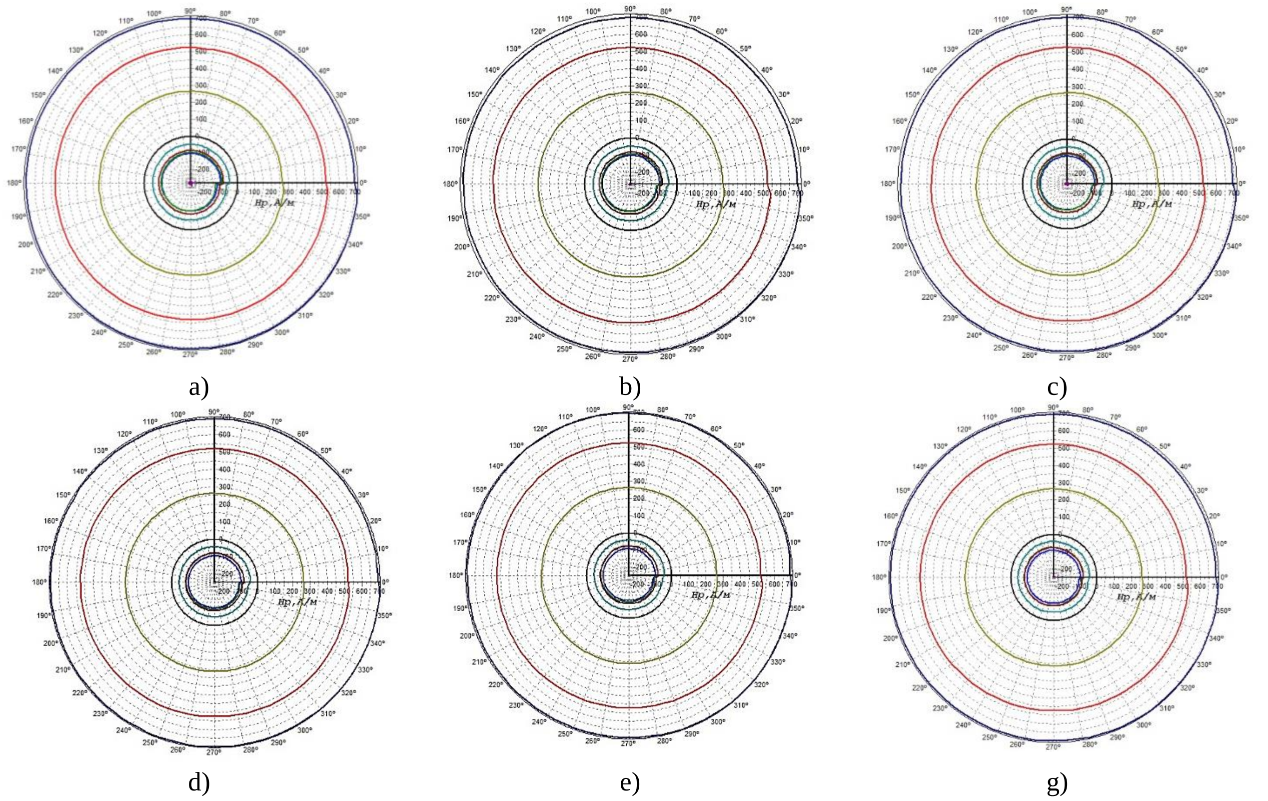
To determine residual stresses, an IKN-3M-12 stress concentration meter (Figure 3) was used. Under the influence of operating or residual mechanical stresses in a ferromagnetic material (in this case, steel), the metal's domain structure undergoes a restructuring. In zones of maximum residual stress (stress concentrations, defects, and structural inhomogeneities), persistent local changes in magnetic permeability occur. These changes create a self-magnetic field, which is "remembered" by the metal and emerges at its surface. The IKN-3M-12 measures the normal component (Hp) of the strength of this self-magnetic stray field on the surface of the tested object. A zero or minimum Hp value or maximum gradient variability of the field (a change in Hp sign) indicates the presence of a zone with high residual stresses.

Fig. 3. – Stress Concentration Meter (IKN-3M-12)
(OOO Energodiagnostika, Moscow, Russia)

For each series, residual stress measurements were performed on individual specimens prepared in accordance with ASTM C633

2. Results and discussion

The results for the series of experiments for three different temperatures (200 °C; 300 °C; 400 °C) and two types of coatings (CRO and NiAlSiCr) are presented in Table 1 and Figures 4, 5.



a) CRO at T= 200 ºC; b) CRO at T= 300 ºC ; c) CRO at T= 400 ºC; d) NiAlSiCr at T= 200 ºC ; e) NiAlSiCrg at T= 300 ºC ; g) NiAlSiCr at T= 4 00 ºC

Рис.4. – Radial diagram of the distribution of magnetic field strength Hp around the tested coating samples

Table 1. Residual stresses of coatings CRO и NiAlSiCr

Series (T,°C)	T_i, °C	$X_1…X_8$ (MPa)	Arithmetic mean $\overline{X_i}$ (MPa)	Dispersion S_i^2 (MPa)
CRO				
1	200	-90; -85; -70; -80; -90;-76;-80; -78	-81.125	41.859
2	300	-50; -55;-42;-30; -35; -40; -32; -30	-36.75	82.9375
3	400	5; 7; -1; 10; 8; -2; -4; 5	3.5	23.25
NiAlSiCr				
1	200	-120, -125, -115, -124, -128, -117, -120, -125	-121.75	18.214
2	300	-65, -50, -45, -64, -68, -55, -50, -45	-55.25	98.786
3	400	-15, -10, 5, 10, -5, 5, 12, 10	1.5	86.857

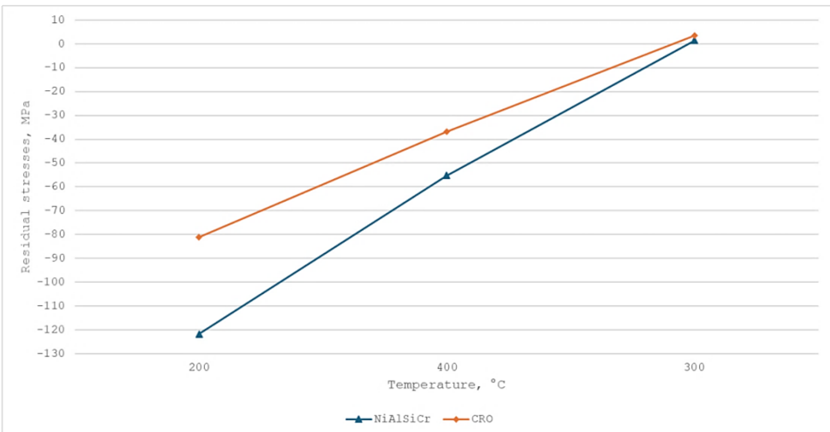


Fig. 5. - Dependence of residual stresses in gas-dynamic coatings on temperature

The graph shows that the CRO coating exhibits lower residual compressive stresses. This can be explained by the fact that CRO is a ceramic coating, which is brittle and exhibits low ductility. During cold gas-dynamic spraying, CRO particles deform significantly less than metal particles. The primary mechanism of coating formation is mechanical adhesion and, possibly, minimal plastic deformation, resulting in lower residual compressive stresses, which typically arise during impact deformation [14].

The NiAlSiCr coating is a metal-composite coating that is ductile. Under high-velocity impact during gas-dynamic spraying, NiAlSiCr particles undergo significant plastic deformation (work hardening) [15]. This deformation is the primary source of residual compressive stresses in cold-sprayed coatings, which are more pronounced than in the CRO coating. To predict, analyze, and manage the mechanical properties of gas-dynamic coatings, regression models were constructed to describe the dependence of residual stresses on temperature.

Since the dependence of residual stresses on temperature on the graph (Fig. 5) appears as a straight line, we use a paired linear regression model in the form:

$$y = a + b \bullet x \tag{1}$$

where y - calculated value of average residual stress, MPa;

x – temperature, °C;

a - free member;

b - regression coefficient.

The regression equations and intermediate data are given in the table 2.

Table 2. Regression analysis of the dependence of residual stresses on temperature in gas-dynamic coatings

Parameter	Coating CRO	Coating NiAlSiCr
Equation	$y = -165.06 + 0.423 \cdot T$	$y = -243.38 + 0.616 \cdot T$
Coefficient b (MPa/°C)	0.423	0.616
Coefficient of determination R^2	0.998	0.997
Statistical significance	Statistically significant because $R^2 \to 1$	Statistically significant because $R^2 \to 1$
The actual value of Fisher's F-test (F_{fact})	699.28	447.53
Critical value of Fisher's F-test (F_{crit})	161.45	161.45
Adequacy	Adequate, because (Ffact > Fcrit)	Adequate, because, ($F_{fact} > F_{crit}$)

Both linear regression equations demonstrate very high adequacy and statistical significance for describing the dependence of the average residual stress on temperature in the studied range (200 - 400 °C).

The coefficients of determination (R^2 = 0.998 for CRO and R^2 = 0.997 for NiAlSiCr) confirm that temperature is the primary factor influencing the average residual stress in both coatings.

In both cases, a direct linear relationship is observed (since the b-coefficient is positive), meaning that as temperature increases, the average residual stress increases (becoming less compressive or more tensile).

Conclusions

The following conclusions were reached as a result of the conducted research:

1) Increasing the working gas temperature during gas-dynamic spraying from 200 °C to 400 °C leads to a sharp decrease in compressive residual stresses (≈ -121.75 MPa) followed by a transition to tensile stresses (≈+3.5 MPa);

2) The determination coefficients R^2_{CRO} ≈ 0.998 (99.8%) and $R^2_{NiAlSiCr}$ ≈ 0.998 (99.7%) confirm that temperature is the determining factor in the formation of residual stresses;

3) The high observed value of the Fisher criterion (F_{fact} ≈ 699.28) compared to the critical value (F_{crit} ≈ 161.45) demonstrates the high adequacy of the constructed regression equation for describing the experimental data;

4) Compressive stresses (-81.125 ÷ -36.75 MPa) for both coatings contribute to increased fatigue strength, but excessively high stresses (-121.75 MPa) can lead to delamination. Zero or low residual stresses are considered optimal for coating stability;

5) A spraying temperature of 400°C is optimal for minimizing residual stresses;

6) The adhesion strength will be further analyzed to finally determine the optimal temperature regime for achieving maximum adhesion strength of the coating to the substrate.

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