Material Properties of Steel with NiCr-Cold Spray Coating

M Chocholousek, Z Spirit, J Brom
Centrum Vyzkumu Rez, CVR, Hlavni 130, Husinec-Rez, Czech Republic
E-mail: michal.chocholousek@cvrez.cz

Abstract. The work is aimed on the NiCr-Cold spray coating applied on GOST 08CH18N10T steel and GOST 22K steel. Cold spray coating shows a high cohesion even as a few millimeter thick layer, therefore it has potential for the repairs not only of the energy industry components. Applied on the steel substrate, the cold spray can be considered as a bimetallic material for the purpose of the mechanical properties evaluation. Performed comparison based on tensile mechanical properties at room temperature and at 350 °C of separate steels and cold spray versus bimetallic combination is discussed. The main goal is to find the optimal approach of bimetallic material evaluation. Additional metallographic and microstructural analysis is attached to show the differences between the used combinations. Influence of possible heat treatment on the mechanical and adhesive properties is also included.

1 Introduction

Cold spray is a promising method of coating formation and the subject of interest of the project solved in Centrum Vyzkumu Réz (CVR). Cold spray is one of many names describing a process for strengthening metals by exposing the substrate to a high-velocity stream of small solid particles accelerated by a supersonic gas nozzle [1]. If the potential of a given method for repairing components by replacing the original material by spraying is evaluated, it is necessary to determine the mechanical properties not only of the coating itself, but also of the substrate-coating combination. The cold spray coating exhibits sufficient strength and adhesion to be tested both alone and in combination with the substrate.

The aim of the project is to verify the applicability of standardized procedures to samples made of tubes and sprays with sufficient thickness and to adapt the methodology for testing thinner layers together with the substrate in cases where it is not possible to produce standard samples. It is also necessary to verify whether the measured mechanical properties of the separate spray correspond to the properties measured and evaluated simultaneously with the substrate. Due to the potential use of the methodology for the energy industry in the Czech Republic, the specimens are also adapted to the European standard EN ISO 6892 [2] and steels used in the energy industry are chosen as substrates. The thickness of the coating can possibly influence the material properties, where the higher thickness can lead to lower ultimate stress due to higher probability of defect occurrence.

Tensile mechanical properties of cold spray layer can be evaluated by various methods [3]: (1) Micro-flat test (MFT) specimens can be manufactured due to the sufficient thickness layer. MFT specimens can be tested according to ASTM E8 standard [4]. (2) Schmidt & coll. developed specific Tubular
coating test (TCT), where a pair of tubes connected with coating is tested. (3) 3- or 4-point bend test can be performed to evaluate the bend mechanical properties of the coating.

2 Material and Methodology

Structural carbon steel GOST 22K and austenitic steel GOST 08CH18N10T were used as substrates for cold spray (CS) deposition. All the cold spray coatings were sprayed at uniform conditions – substrate surface preparation, NiCr powder [5] of chosen grain size (5-25 μm), nitrogen gas, angle of deposition and the spraying parameters (intellectual property of Impact Innovations GmbH company).

The tensile specimens were prepared as proportional specimens according to EN ISO 6862 from substrate materials and for substrate-cold spray combination (figure 1), where the cold spray was sprayed as approximately 1.2 mm thick layer on 4 mm diameter substrate. Flat specimens of 3.5 mm thickness were used for material properties evaluation of the cold spray without substrate. Flat specimens were evaluated as proportional too. The shape of specimens was chosen due to the suitability for cold spraying and due to the simple evaluation (i.e. the thickness measurement before and after the coating) compared to the shape of tube segments.

The specimens were heat treated (HT1) at 640 °C (limit temperature for the austenitic pipe lines due to the risk of microstructural changes) for 1 hour (i.e. holding time 10 min/1 mm of specimen thickness), the heating speed 80 °C/hour and the cooling speed 30 °C/hour. Considering low influence of HT on mechanical properties of steel-CS specimens after tensile tests, flat specimens of cold spray without substrate were heat treated with 12 hours holding time (HT12). The maximal temperature for HT was set due to considering theoretical application in industry.

![Figure 1. Proportional specimens of substrate-cold spray for tensile testing.](image)

The tensile tests were performed on the universal testing machine Zwick/Roell Z250 with the laser extensometer at temperatures 24 °C and 350 °C. Material properties of substrates were evaluated according to standards. The tensile test of specimens substrate-cold spray were stopped after coating’s rupture.

The specimen substrate-cold spray can be ideally considered as two parallel specimens from different materials, those are under uniaxial tension stress. Both materials have equal deformation (i.e. elongation in the tensile direction) due to specimen’s compactness. Total force is given by the sum of partial forces in both materials (i.e. \( F = F_1 + F_2 \), where index 1 is for substrate and index 2 is for cold-spray coating). By relating the force to the initial cross-section \( S_0 \), where \( S_0 = S_{01} + S_{02} \) (sum of the cross-sections of both materials), the total stress of the tested pair can be expressed as

\[
\sigma = \frac{S_{01}}{S_0} \sigma_1 + \frac{S_{02}}{S_0} \sigma_2 \quad (1)
\]

According to equation (1), the total stress of the sample is given by the weighted average of individual stresses at a given deformation and the weight of the stress contribution is given by the ratio of the initial cross-section of the given material to the total initial cross-section. After measuring the total fracture stress and knowledge of the stress-strain characteristics of the substrate, it is possible to determine the stress of the substrate for the given deformation and evaluate the theoretical stresses of the cold spray layer \( \sigma_2 \).
Results and discussion
In the case of threaded rod-shaped specimen (figure 2), the cold spray layer usually breaks at the point where the radius of transition from the test part of the body to the threaded head is. The cold spray layer is thinned there and due to the changing cross-section of both the substrate and the cold spray layer, the resulting stresses (table 1) may be lower than expected. Informative values for calculated stresses of the cold spray layer are given in table 2.

Table 1. Ultimate tensile strength (UTS) of tested materials (substrates with and without cold spray).

| Material                  | T (°C) | UTS (MPa) | UTS standard deviation (MPa) | σ₀.₁ (MPa) | σ₀.₁ standard deviation (MPa) |
|---------------------------|--------|-----------|------------------------------|------------|------------------------------|
| 08CH18N10T                | 24     | 552       | 4                            | 249        | 3                            |
| 08CH18N10T                | 350    | 405       | 3                            | 211        | 7                            |
| 08CH18N10T (HT1)          | 24     | 587       | 1                            | 249        | 6                            |
| 08CH18N10T (HT1)          | 350    | 426       | 0                            | 171        | 3                            |
| 22K                       | 24     | 537       | 1                            | 389        | 13                           |
| 22K                       | 350    | 513       | 1                            | 262        | 1                            |
| 08CH18N10T + CS           | 24     | 577       | 21                           | -          | -                            |
| 08CH18N10T + CS           | 350    | 443       | 21                           | -          | -                            |
| 22K + CS                  | 24     | 585       | 12                           | -          | -                            |
| 22K + CS                  | 350    | 511       | 27                           | -          | -                            |
| 08CH18N10T + CS (HT1)     | 24     | 633       | 28                           | -          | -                            |
| 08CH18N10T + CS (HT1)     | 350    | 532       | 25                           | -          | -                            |
| 22K + CS (HT1)            | 24     | 682       | 8                            | -          | -                            |
| 22K + CS (HT1)            | 350    | 584       | 14                           | -          | -                            |

Despite the fact that the chosen specimen shape is not the optimal for the evaluation, the cold spray layer shows compactness and higher tensile stress values than the substrates. The values calculated using equation (1) need precise stress value of substrate steel at cold spray rupture as an input for evaluation. The stress value is given by the particular deformation.

Plastic elongation of cold spray layer without heat treatment is low (approx. 0.1 %), thus the substrate values of stress at 0.1 % elongation is given too (table 1).

Comparing the substrate and cold spray stresses, the mechanical properties of the coating are significantly higher. The specimen with cold spray is a compact material capable to withstand higher stresses than the substrate itself.

The elongation of NiCr cold spray without heat treatment is negligible (approx. 0.1 %) due to brittleness of the coating. The used heat treatment increases the elongation at rupture to 0.6 % at room temperature for specimens from steel 22K with NiCr cold spray, however the tests at 350 °C shows decrease to 0.2% elongation. The equal heat treatment (640 °C, 1 hour holding time) used on...
specimens from steel 08CH18N10T with cold spray coating had negligible influence on elongation results.

Table 2. Ultimate tensile strength (UTS) of cold spray (from specimens with and without substrate).

| Material                  | T (°C) | UTS (MPa) | UTS standard deviation (MPa) |
|---------------------------|--------|-----------|------------------------------|
| NiCr (CS)                 | 24     | 494       | 55                           |
| NiCr (CS)                 | 350    | 425       | 30                           |
| NiCr (CS, HT12)           | 24     | 779       | 7                            |
| NiCr (CS, HT12)           | 350    | 684       | 8                            |
| NiCr (08CH18N10T + CS)    | 24     | 783       | 33                           |
| NiCr (08CH18N10T + CS)    | 350    | 615       | 33                           |
| NiCr (08CH18N10T + CS, HT1)| 24   | 869       | 38                           |
| NiCr (08CH18N10T + CS, HT1)| 350 | 733       | 44                           |
| NiCr (22K + CS)           | 24     | 706       | 21                           |
| NiCr (22K + CS)           | 350    | 662       | 41                           |
| NiCr (22K + CS, HT1)      | 24     | 862       | 13                           |
| NiCr (22K + CS, HT1)      | 350    | 771       | 22                           |

4 Conclusion

Tensile tests on 08CH18N10T and 22K steel specimens with and without NiCr cold spray coating were performed to evaluate mechanical properties of the cold spray layer. Tensile test of flat specimens were performed on NiCr cold spray without steel substrate. All tests were performed at room temperature and 350 °C. Influence of heat treatment at 640 °C on cold spray layer was confirmed, however the influence decreases with increase of tensile test temperature.

NiCr cold spray is suitable material to be tested (according to tensile ASTM/ISO standards) without substrate in case of several millimeter thicknesses. Though NiCr cold spray without heat treatment shows higher mechanical properties when it is tested with substrate steel. Therefore the specimens substrate-cold spray are appropriate for tensile testing, especially in case of coating thickness insufficient for standard specimens manufacturing.

The shape of substrate-cold spray specimen is recommended to be flat or tube segment. The standard rod-shape specimen with threads is not recommended due to potential rupture of cold spray in radius. NiCr cold spray increases mechanical properties of used steels. It confirms the compactness of the cold spray coating.

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