

Martin Vicen ✉
Libor Trško
Otakar Bokůvka
Eva Nogová
Anna Góral
Wojciech Żórawski

<https://doi.org/10.21278/TOF.502080625>
ISSN 1333-1124
eISSN 1849-1391

IMPROVEMENT OF TITANIUM COLD SPRAY COATING ADHESION BY SHOT PEENING

Summary

Shot peening was applied to quenched and highly tempered C55 structural steel as a pre-treatment to titanium coating cold spray deposition with the aim of improving the coating's adhesion during cyclic loading. Applying titanium cold spray directly onto the steel surface caused significant plastic deformation of the substrate, resulting in the creation of discontinuities on the coating/substrate interface. When shot peening was applied prior to the cold spraying, the work-hardened surface layer served as a more suitable substrate, avoiding the creation of major interface discontinuities. Fatigue resistance of the shot-peened specimens was improved by up to 20% and no coating delamination was observed in the regions of fatigue crack initiation and propagation.

Key words: cold spray; Ti coating; adhesion; shot peening; fatigue

1. Introduction

Carbon steels are preferred engineering structural materials mainly due to their favourable properties such as high toughness, hardness, good machinability, and low costs. Thanks to these properties, they are widely used in mechanical and civil engineering, transport, energetics, and chemical engineering [1,2]. Besides their unfavourable strength/weight ratio, their main disadvantage is low corrosion resistance which causes a high rate of surface oxidation, coupled with decreasing mechanical properties over the application time. Implementing effective surface treatments that prevent corrosion could lead to significant savings in maintenance and repairs [1,3,4]. Modern approaches to improve the corrosion resistance of carbon steels are based on the application of corrosion inhibitors, which constitutes an easily applicable and cheap solution for this corrosion issue. The authors in [3] confirmed the effectiveness of this method when, with the use of organic dimethylaminoethanol (DMEA), they achieved a significant reduction in the corrosion rate of carbon steel. However, inhibitors create only thin surface layers through chemical reactions with the substrate with little resistance to wear or mechanical loading. Therefore, more robust surface treatments are required in engineering applications to withstand the severe loading conditions experienced by carbon steel components.

Gas dynamic cold spraying (CS) is considered a relatively new coating deposition technology, which achieves dense, high-quality layers with low oxygen content and strong coating to substrate adhesion. The main advantage of the method is avoiding substrate back annealing or solution annealing, as the process is performed at low temperatures while using high particle velocities. This distinguishes it from other surface-coating techniques such as thermal spraying, where significant substrate heating occurs during the deposition process [5]. This consequently makes CS a promising method for the renewal, repair, and protection of damaged components using metallic powders. The results also show that the process can preserve the required properties of the repaired component when compared to the original base materials [6,7].

Titanium and its alloys have drawn interest due to their unique combination of functional and structural properties, including their favourable strength to weight ratio. These alloys also exhibit good corrosion resistance both in common and even more aggressive environments, along with biocompatibility and low toxicity [8-13]. Thanks to these properties, titanium is desirable for applications in the aeronautic, biomedical, and energetic industries. However, pure titanium has significant limitations such as a low yield point and fatigue resistance, as well as mediocre fracture toughness [11]. This has led to the addition of β -phase stabilising elements which have resulted in a significant improvement in its mechanical properties, giving a baseline for the development of modern grades of titanium alloys [12-14].

Methods for pure titanium coating deposition can be divided into two main techniques. The first is characterised by deposition temperatures which lead to the melting of the titanium powder, and the second involves deposition temperatures lower than the melting point. The first group includes conventional methods, such as High Velocity Oxy-Fuel (HVOF), laser plating, and plasma spraying. The second group exclusively involves the gas dynamic cold spraying process where the lower process temperatures are compensated for by the high velocity of particles that often exceed supersonic speeds. The high velocity impact on the substrate leads to mutual bonding with the substrate through the creation of micro and nano welds. This unique process allows for the deposition of commercially pure titanium on a wide scale of substrates, including high-strength steels without losing superior mechanical properties by annealing. This permits the manufacturing of coatings with high thickness, low porosity, and a controlled microstructure [15,16]. Increased interest is also being paid to CS coatings of pure titanium aimed at substrate corrosion protection, mainly in aqueous environments, where electro-chemical corrosion mechanisms can take place. Low porosity in the coating of pure Ti plays a key role in forming a highly corrosion-resistant barrier between the substrate and the corrosive environment [17].

The majority of studies related to substrate-coating adhesion have been aimed at the interaction between the particles and the substrate which both have similar mechanical properties. Achieving good adhesion between identical materials (e.g. titanium on titanium) is not as challenging as for dissimilar coatings, where the coating is processed on substrates with different chemical and mechanical characteristics (e.g. aluminium on steel). This is due to the mutual deformation of the particles and the substrate when the chemical and mechanical properties are very similar. The process becomes even more challenging in the case of dissimilar deposition when, typically, softer particles like Al and Cu are deposited on hard substrates such as steels. Multiple studies [18-23] have shown that the adhesion of soft materials on harder substrates is influenced mainly by the hardness and roughness of the substrate. Stoltenhoff et al. [18] stated that the adhesion of cold sprayed copper is always better on softer substrates (e.g. Al or Cu) than on harder ones (e.g. steels). More detailed studies have indicated that soft particle adhesion on steel substrates can be improved by increasing the surface roughness up to a threshold value, which is related to the ratio between the particle size and surface topography parameters. In the case of cold sprayed brass on steel, Theimer et al. [19] stated that maximal bond strength was found for a surface roughness R_z that corresponds to d_{80} of the powder size distribution, roughly meeting the lateral dimensions of deformed

particles close to the interface. In contrast, Kumar et al. [20] suggested for aluminium depositions on soft steel a slightly lower roughness threshold which lies between $R_z = 0.5$ and $R_z = 0.75$ of the particles' mean size. Samson et al. [24] claimed that the adhesion of soft coating (pure Al) on slightly harder substrates (AA6061 aluminium alloy) can be improved by increasing the surface roughness. However, they did not indicate any direct correlation between surface topography and particle size. In the majority of works, improved coating adhesion has been attributed to the increased number of features which are suitable for the better mechanical "locking" of the particles combined with the effect of compressive residual stress accumulation.

A different opinion on substrate roughness before the application of CS is given in [25]. The results of coating adhesion tests showed that smoother surfaces improved the bonding of Ti-6Al-4V deposited on Ti-6Al-4V from 7.1 MPa ($R_a = 5.4 \mu\text{m}$, failure at the interface) to 68.7 MPa ($R_a = 0.05 \mu\text{m}$, cohesive failure). The work of Kumar et al. [26] concludes that the mirror-polished condition of the SS316L substrate provides better adhesion with a cold sprayed ceramics coating than as-received and semi-polished conditions.

Conflicting findings in the published results regarding the relationship between the substrate's roughness and coating adhesion have created uncertainty about setting up proper process parameters to achieve the best performance. The aim of this work is therefore to study the effect of increased surface roughness by shot peening treatment applied to the steel surface prior to CS deposition of a titanium coating on its adhesion and integrity when subjected to cyclic loading. The ultimate goal is to be able to use titanium CS coating as a corrosion protective barrier on steel components which need to withstand mechanical loading without cracking or delamination.

2. Experimental material and coating deposition

C55 carbon steel was used as the experimental material, with its chemical composition shown in Table 1. The steel was heat treated by quenching and high tempering: austenitisation at 840 °C for 40 minutes followed by water quenching, and tempering at 420 °C for 180 minutes with subsequent air cooling. The resulting mechanical properties of the material after the heat treatment are given in Table 2. The steel's microstructure (Fig. 1) was formed by highly tempered martensite and retained austenite.

Table 1 Chemical composition of C55 steel (wt. %).

Steel grade	Chemical composition								
	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
Part analysis	0.597	0.368	0.800	0.037	0.014	0.245	0.193	-	Bal.
Requirement per steel standard	0.52 – 0.60	0.17 – 0.37	0.50 – 0.80	max. 0.040	max. 0.040	max. 0.25	max. 0.30	max. 0.30	Bal.

Table 2 Mechanical properties of the C55 steel after heat treatment.

UTS /MPa	Yield point /MPa	Ductility /%	Hardness HV1
1320	1240	13	440

Two sets of fatigue test specimens (6 pcs each) were machined with geometry as shown in Fig. 2. The first set was used for the direct cold spray coating deposition of pure titanium on the machined surface. The second set was first shot peened with S170 steel balls (diameter of 0.42 mm, hardness range 40 – 50 HRC) with an Almen intensity of 12 A and 100% coverage, after which a cold spray titanium coating deposition was performed. The shot peening process was performed in an automated industrial peening machine at Peen Service, S.r.l., Bologna, Italy.

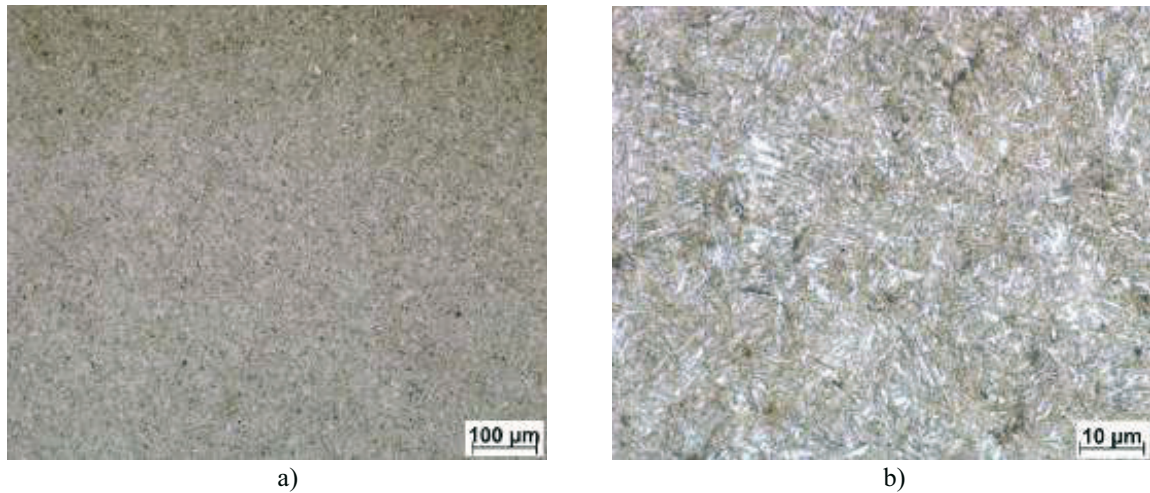


Fig. 1 Microstructure of the C55 steel after heat treatment, etch. 1% Nital: a) overview, b) detail.

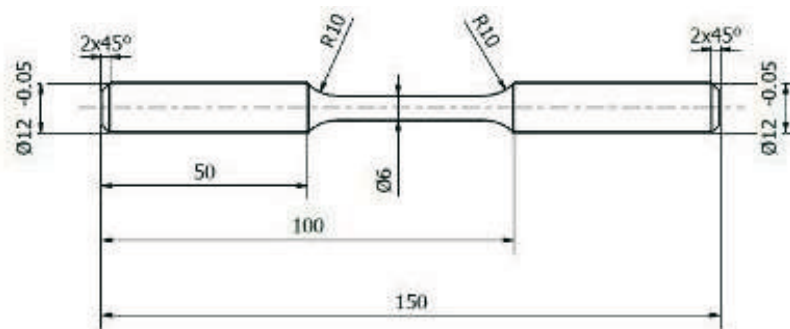


Fig. 2 Geometry of fatigue test specimen.

The cold spray process was performed using Titanium powder with a 99 wt.% Ti content feedstock (produced using the hydride-dehydride method) at Kielce University of Technology, utilising an Impact Innovations 5/8 System (Impact-Innovations GmbH, Rattenkirchen, Germany) in collaboration with a Fanuc M-20iA robot (Fanuc Robotics Ltd., Oshino, Japan). To achieve the highest possible velocity and temperature of the titanium powder particles, the system was set to its maximum parameters: 800°C and 40 bar pressure. Nitrogen gas was employed during the process with a 30 mm stand-off distance from the surface of the specimen. To ensure consistent results, the whole set of specimens was mounted in a multi-spindle device and sprayed simultaneously. The nozzle's traverse speed was set to 10 mm/s, while the fatigue specimens rotated at 1500 rpm. After depositing five layers, the diameter of the samples increased from 6 mm to the planned 8 mm. During the deposition, the specimens were cooled, maintaining a temperature below 80°C.

3. Testing methodology

The surface roughness prior to and after the coating deposition was evaluated using a MarSurf PS10 roughness tester in accordance with ISO 21920. The data were evaluated as an arithmetical average of three measurements performed at different locations on the specimen's circumference.

The particle size distribution of the Ti powder was measured using a HELOS H2398 laser diffractometer. The phase composition of the powder and coatings was analysed with a Bruker D8 Discover diffractometer using Co-K α radiation ($\lambda = 1.78897 \text{ \AA}$). The phase analysis was performed using Diffrac EVA 3.0 software with the PDF-4 crystallographic database.

The residual stress state of the machined and shot peened specimens was evaluated using the X-ray diffraction technique. A ProtoiXRD device was used for the analysis, using CrK α radiation with an irradiated area of 1 mm². The diffraction signal from {222} α planes was collected at $2\theta = 156.9^\circ$. The measurements were carried out using the $\sin^2\psi$ method, with nine inclinations between $\pm 39^\circ$. The measurements were performed in axial ($\varphi = 0^\circ$) and tangential ($\varphi = 90^\circ$) directions. To obtain the depth profile of the residual stress distribution, the surface was gradually removed by electrolytic polishing.

Fatigue life analysis was performed with the use of rotary-bending loading in accordance with ISO 1143 at 30 Hz loading frequency, room temperature, and a cycle asymmetry ratio of $R = -1$. Testing was done in a stress-controlled regime. The aim was to evaluate the effect of Titanium cold spray coating in potential combination with shot peening on the steel's fatigue performance and to obtain information on the coating adhesion and integrity under repeated mechanical loading. Although the number of available samples was quite limited and the results do not provide large datasets, the S – N curves already provide an indication of the fatigue behaviour. The fatigue test data were evaluated by the Basquin function (1) with the use of the least square method:

$$\sigma_a = \sigma'_f (N_f)^b, \quad (1)$$

where b is the exponent of the fatigue life curve and σ'_f is the coefficient of fatigue toughness obtained by the extrapolation of stress amplitude on the first loading cycle [27]. Due to the different test termination conditions of the run-out specimens, only specimens which ended with a fracture were considered for the Basquin evaluation.

An analysis of the fracture surface together with the surface chemical composition was performed with the use of a ThermoScientific Phenom XL scanning electron microscope (SEM) equipped with an Energy-Dispersive X-ray detector (EDX).

4. Results

4.1 Roughness evaluation

The results of the roughness evaluation given in Table 3 show that shot peening significantly increased the surface roughness. This is an expected effect of the peening treatment and is a standard accompanying phenomenon [28]. The substrate surface roughness appears not to have influenced the roughness of the Ti cold sprayed coating, as the roughness of both coatings are identical. This indicates that in the case of thick coatings formed by multiple deposition layers, at a certain point the coating stops copying the initial surface roughness.

Table 3 Roughness of the specimens before and after Titanium cold spray deposition.

	Roughness parameter	As-machined	Shot peened	As-machined + Ti coating	Shot peened + Ti coating
Average value	$Ra / \mu\text{m}$	0.422	2.226	10.706	10.443
	$Rz / \mu\text{m}$	3.856	11.942	56.919	56.780

4.2 Residual stress analysis

The results (Fig. 3) show that both surface finishings (machining and shot peening) introduced compressive residual stresses in the surface and near-surface regions of the fatigue test specimens. The generated stresses have a similar compressive maximum; however, the depth of the residual stress field after shot peening is significantly deeper than that after machining.

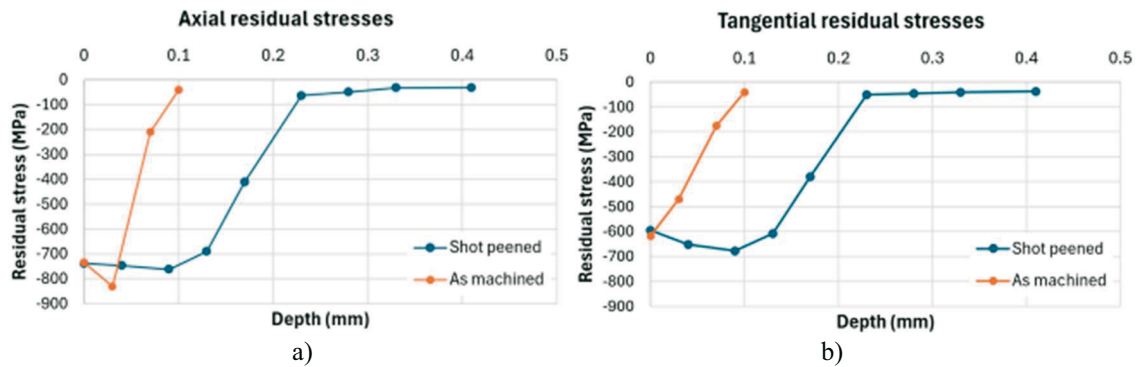


Fig. 3 Residual stress profiles of the as-machined and shot peened fatigue test specimens: a) in the axial direction, b) in the tangential direction.

4.3 Titanium powder analysis

The titanium powder used in the experiment consists of irregular and angular particles due to its production through the hydride-dehydride process (Fig. 4a). The cross-sectional view in Fig. 4b shows that the titanium grains are uniform and free from inclusions or internal porosity. An analysis of the powder's particle size distribution revealed the following parameters: $d_{10} = 18.00 \mu\text{m}$, $d_{50} = 35.00 \mu\text{m}$, and $d_{90} = 60.00 \mu\text{m}$ (Fig. 5). The X-ray diffraction patterns for the titanium powder, shown in Fig. 6, confirm that the powder is composed of pure crystalline titanium (Fig. 6).

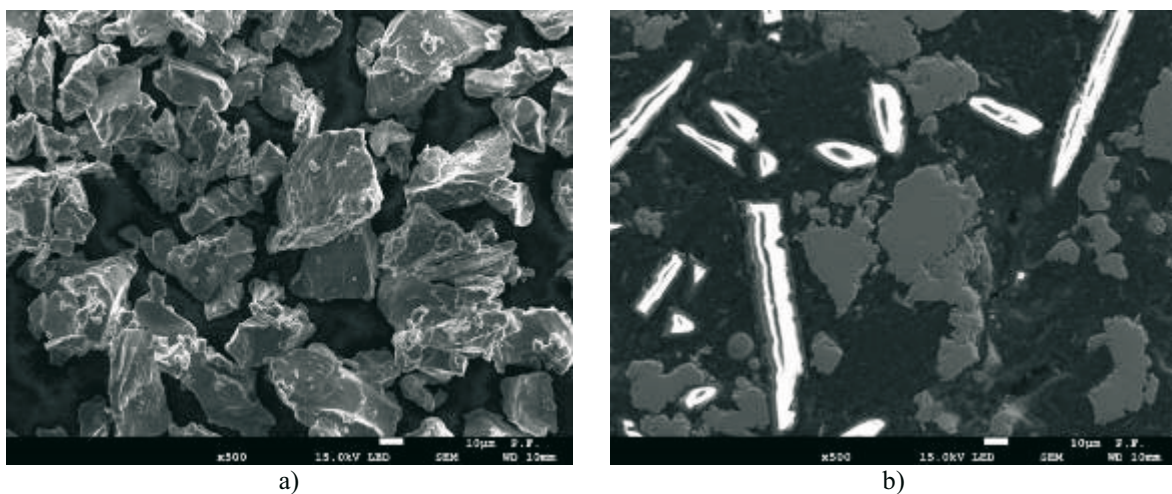


Fig. 4 Ti powder grains: a) morphology, b) cross-section.

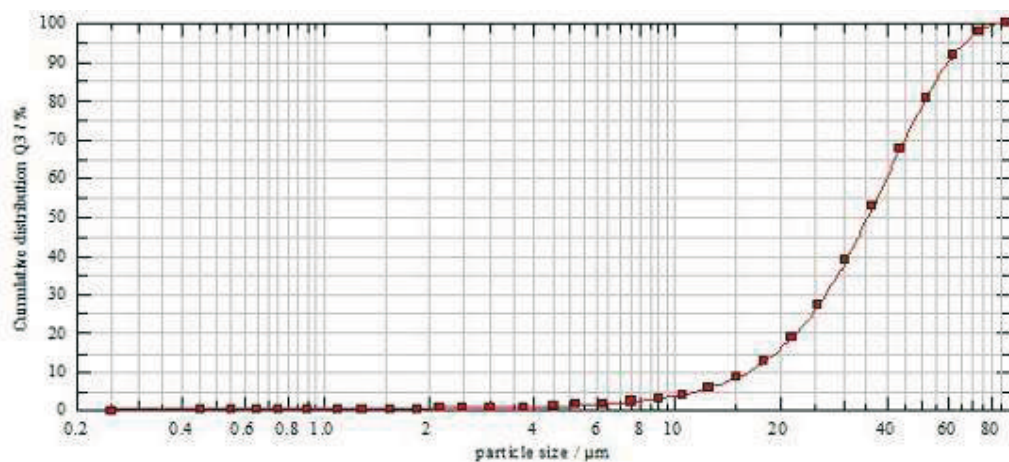


Fig. 5 Grain size distribution of Ti powder.

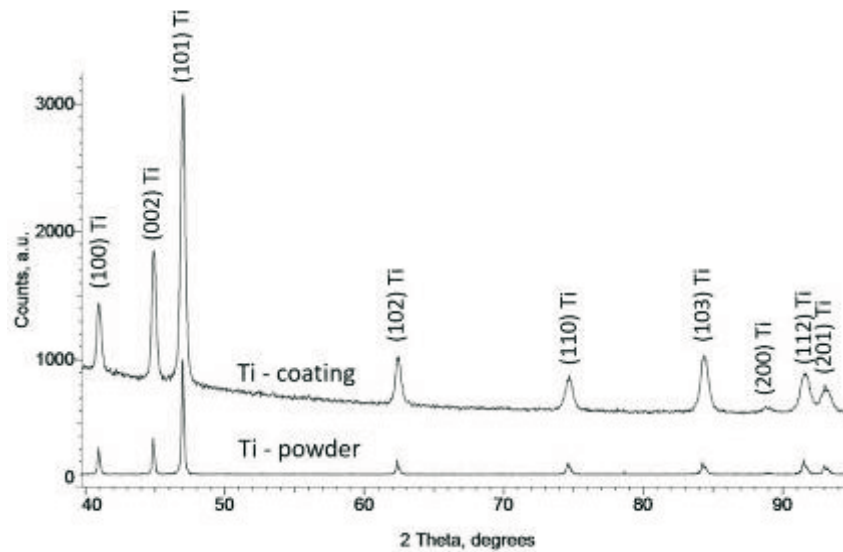


Fig. 6 XRD phase analysis of Ti powder.

4.4 Coating characterisation

The microstructure of the titanium coating is presented in its cross-section in Fig. 7. The coating features a small number of very fine pores that are evenly distributed throughout the entire cross-sectional area (Fig. 7a). This is further confirmed by examining the etched cross-section of the coating, which reveals its microstructure (Fig. 7b). The substantial deformation of all powder grains is clearly visible, regardless of their size. Due to impact with the substrate, the deformed powder grains create large bonding areas with minimal porosity. This effect is attributed to the adiabatic shear phenomenon, which generates high temperatures and local melting between the depositing titanium powder particles. The XRD results show that no new phases are formed in the titanium coating (Fig. 6). The cold sprayed coatings contain only the same crystalline phase as the original feedstock.

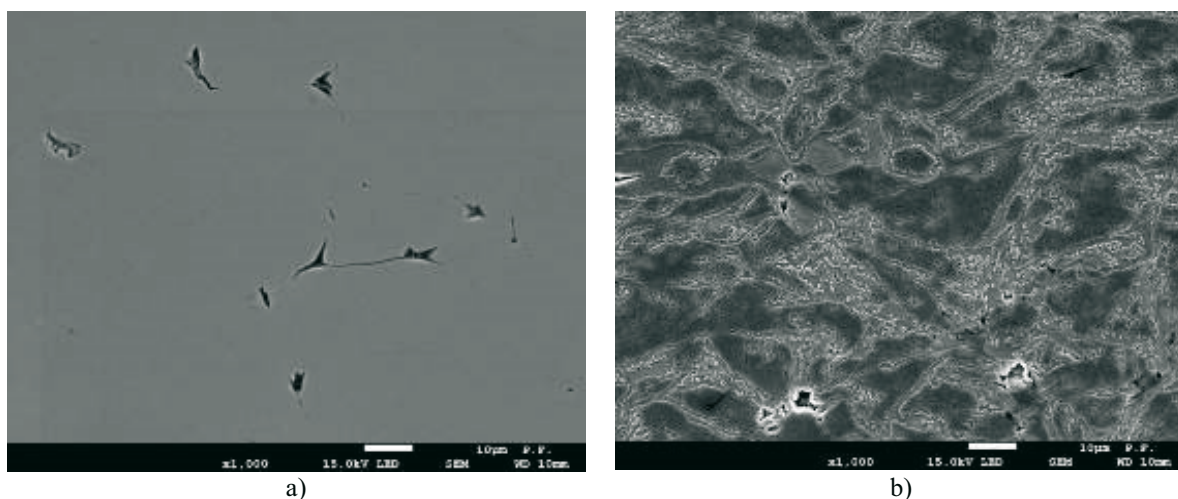


Fig. 7 Ti cold sprayed coating: a) cross-section, b) etched cross-section.

Metallography analysis of the transversal section of the fatigue test specimens showed large voids on the coating/substrate interface of the machined and coated specimens (Fig. 8a). In contrast, no such voids are observed on the shot peened and coated specimen, and the overall coating adhesion is improved (Fig. 8b). The roughness of the substrate coating interface of the as-machined specimens appears higher than the prior shot peened one (Fig. 8).

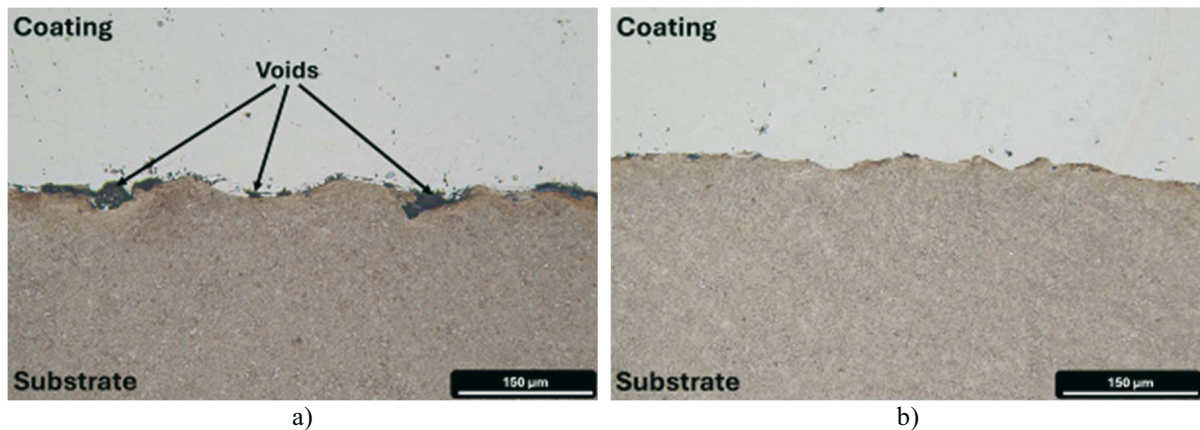


Fig. 8 Interface between the coating and the substrate of specimen: a) as-machined, b) shot peened.

4.5 Fatigue life and coating integrity analysis

Although the number of available specimens was limited and the results do not provide a large statistical dataset, from the trends of the S-N curves a mild increase in the fatigue performance can be seen when shot peening was applied prior to the deposition of Titanium cold spray coating. The level of improvement is not identical in the whole range of the number of loading cycles where, for the number of cycles to fracture near $N = 10^5$, the improvement is less evident and reaches only about 5%. In contrast, the difference in the run-out stress levels for $N = 10^7$ loading cycles is 84 MPa, which represents a fatigue limit increase of 28.7% (Fig. 9).

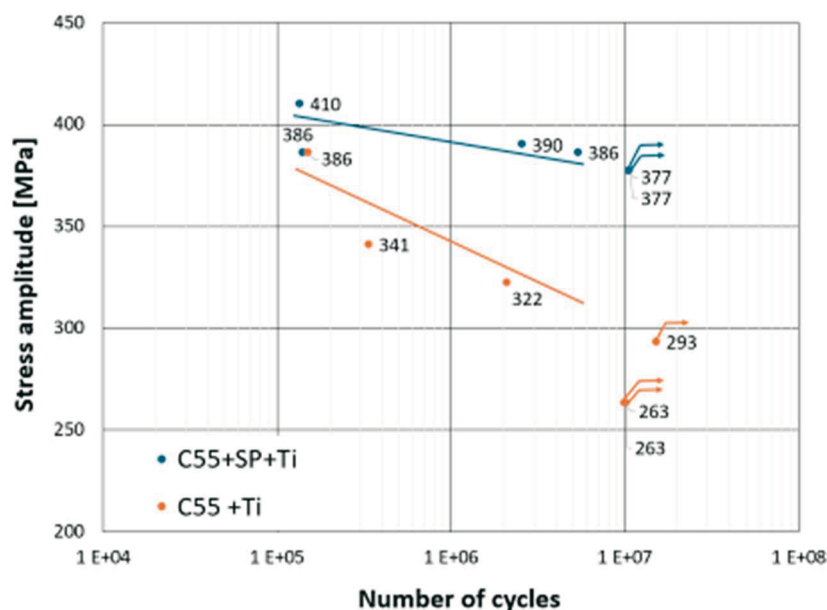


Fig. 9 S-N curves of cold sprayed C55 steel with and without the application of shot peening.

A fracture surface analysis of specimens fractured at stress levels corresponding to failure near $N = 10^5$ loading cycles revealed that the adhesion of the Ti cold spray on the C55 machined steel was poor, and the coating completely separated from the substrate (Fig. 10a). The Ti coating fracture surface clearly shows fatigue features (Fig. 10b,c); however, the position of the coating's fracture does not match the position of the C55 substrate rod fracture. This indicates that the fatigue process took place independently in the coating and in the steel substrate. In the C55 steel rod, the fatigue crack initiation site exhibits severe damage due to local contact (Fig. 10d). Nevertheless, it can be seen that the fatigue features spread from a near-surface area,

indicating that the fatigue crack initiation occurred on the steel surface (Fig. 10e). No unambiguous evidence of the fatigue crack initiation location was found on the Ti coating fracture surface. Therefore, it was not possible to determine if the fatigue crack propagated from the surface towards to the interface or vice versa.

The surface of the C55 steel rod after deposition of the cold spray Ti coating shows marks of plastic deformation caused by the impacts of the titanium particles at high velocity (Fig. 11a). The EDX mapping depicted in Fig. 11b indicates remnants of titanium on the steel surface, showing that the coating deposition resulted in some material transfer. However, this was insufficient for proper coating adhesion.

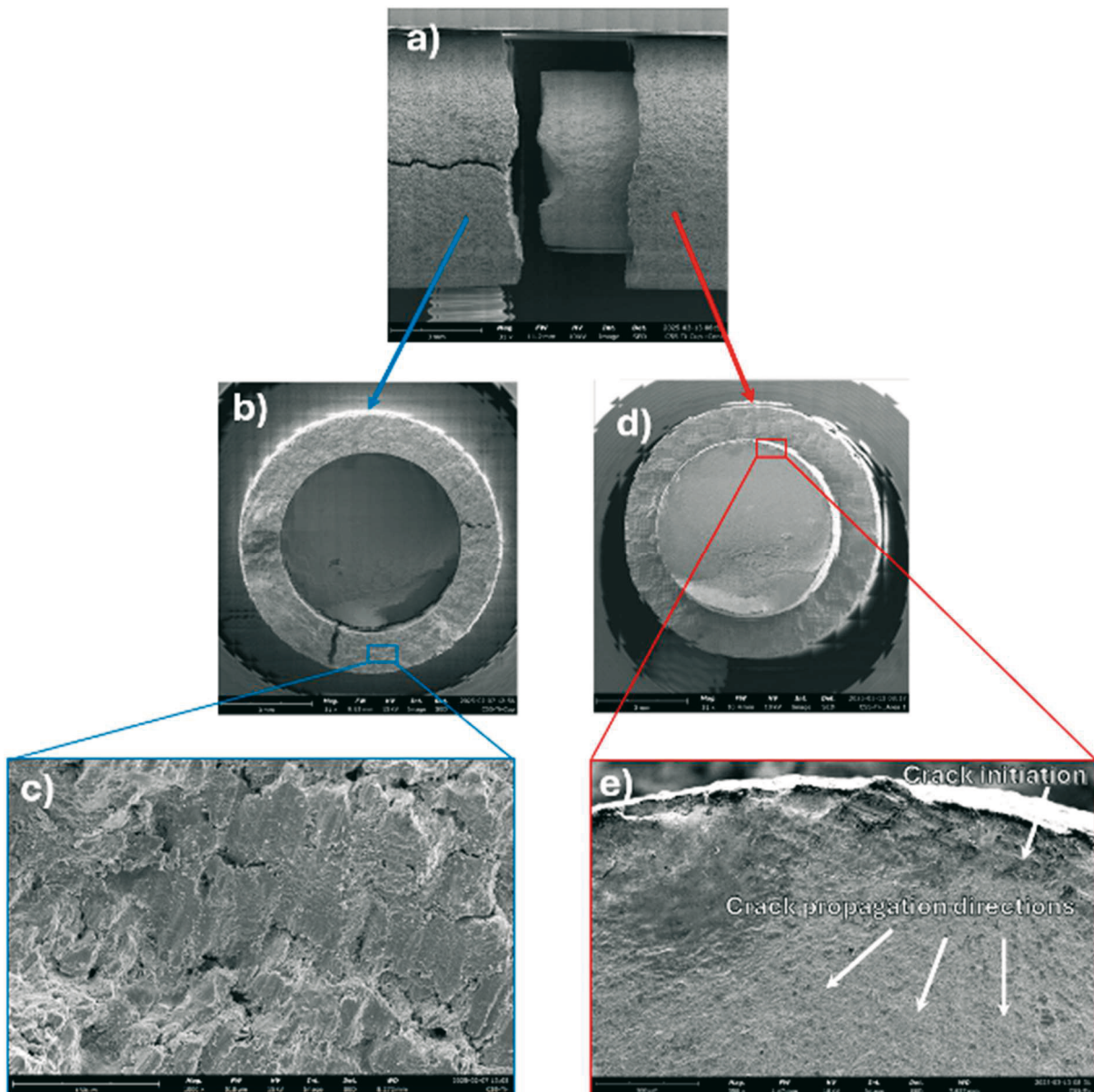


Fig. 10 Fracture surface analysis of C55+Ti.

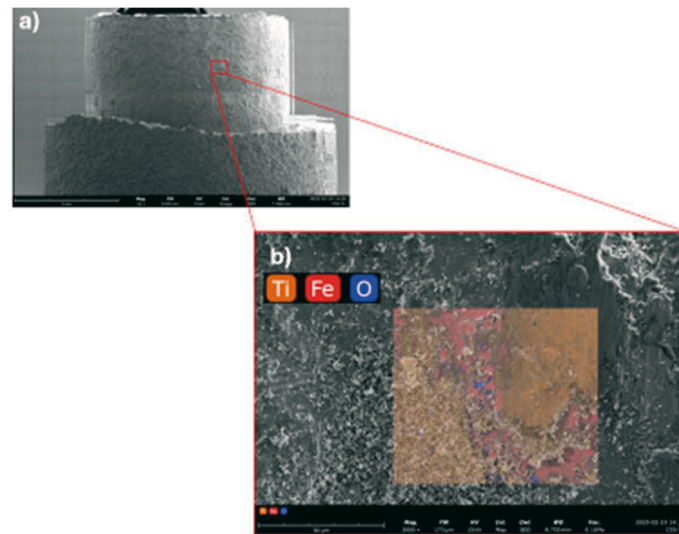


Fig. 11 EDX mapping C55+Ti specimen after fatigue test.

When shot peening was performed prior to the cold spray Ti deposition, the fatigue fracture of the coating and the steel rod occurred in the same plane (Fig. 12a), confirming improved titanium adhesion to the substrate. The fatigue crack initiation occurred on the interface between the coating and the substrate (Fig. 12b, c) and propagated towards the core of the steel rod. In this case, the titanium coating fracture surface does not possess clear fatigue features, and the fracture is most likely a result of static overload. It is important to note that there is no visible coating delamination near the fatigue crack initiation area (Fig. 12c). The only coating delamination was observed near the final fracture area (Fig. 12d), where the layer was peeled off due to bending overload. On the interface between the substrate and the coating, in the final fracture area, a thin surface layer with a flat appearance can be observed, which corresponds to the work-hardened surface layer created by the shot peening process. Again, no clear location of fatigue crack initiation was observed on the coating, and thus it was not possible to evaluate the direction of fatigue crack propagation.

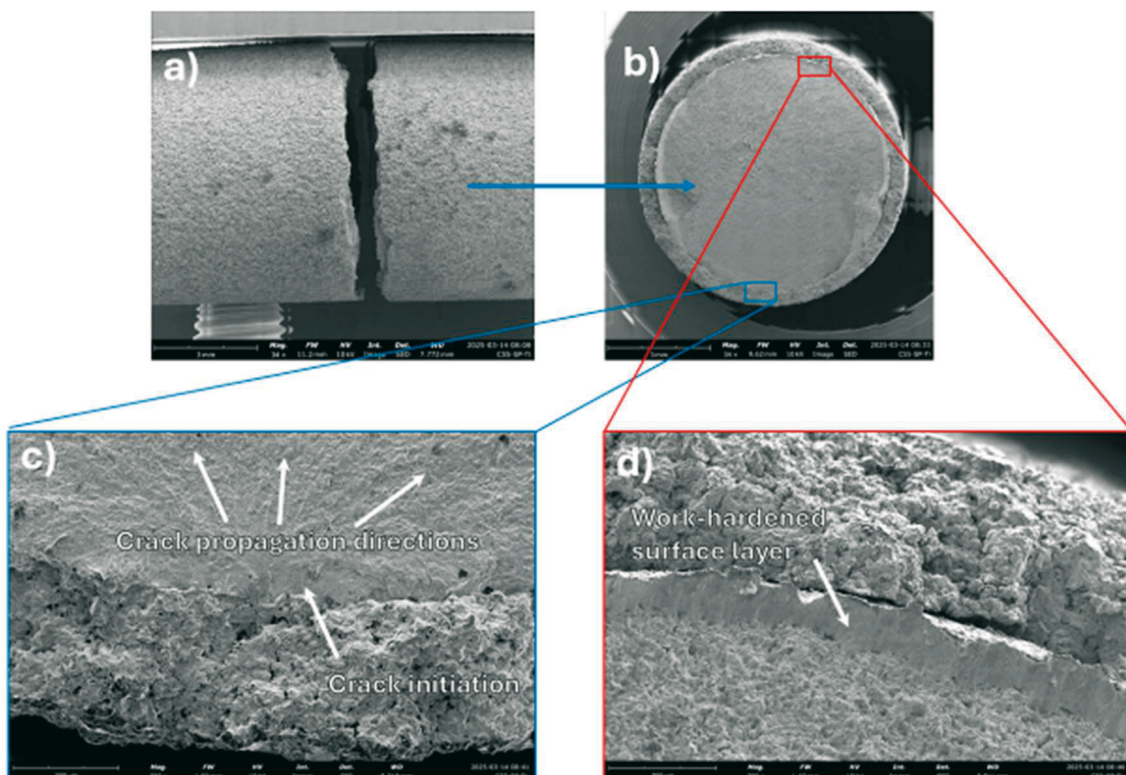


Fig. 12 Fracture surface analysis of C55+SP+Ti.

5. Discussion

This study of the coating-substrate interface by means of a cross-sectional metallography analysis (Fig. 8) has revealed that for purely quenched and tempered steel, the particle impacts during the coating deposition induced local plastic deformation of the surface. Due to the high velocity impacts, the substrate surface roughness appears significantly greater than that produced by shot peening, despite the fact that originally the opposite was the case (Table 3). However, this could not be confirmed by direct roughness measurements, as they would require peeling off the coating without any effect on the substrate. The process resulted in the creation of large discontinuities (voids) on the interface (Fig. 8a) which apparently led to poor coating adhesion on the substrate. During the fatigue loading, the coating behaved as an independent solid where the fatigue process took place separately from the substrate (Fig. 10). A similar cold sprayed layer delamination mechanism was observed in the work of Bond [29] where interfacial debonding was observed due to the mechanical loading of the 6061 aluminium alloy.

When shot peening was performed prior to titanium cold spray deposition, the work-hardened surface layer served as a more suitable interface for particle bonding. Even when the initial surface roughness was much higher than for the as-machined specimens (Table 3), the interface roughness appears to be much lower, containing only minor discontinuities (Fig. 8). This can be attributed to a higher level of work hardening of the shot peened layer as the titanium particles during the coating process were not able to significantly deform the impact area. In fact, the increased surface roughness prior to cold spray deposition proved to be beneficial to the coating adhesion, as stated in [19, 24]. The reason is related to maximising the surface contact area and providing a higher number of pinning points with the uneven surface. The authors in [19] even concluded that the optimal surface roughness R_z is 0.75 times the mean particle size, which provides the maximal contact between the impacting particles and the substrate.

During the fatigue loading of the prior shot peened and cold sprayed specimens, the fatigue crack initiation occurred under the coating, in the steel substrate (Fig. 12). From this point, it propagated towards the core of the specimen. This indicates that the coating and the substrate behaved as a more uniform solid as no coating delamination can be observed near the fatigue crack initiation site. Improved coating adhesion is crucial in engineering applications as mechanical loading of the coating with poor adhesion causes its mechanical degradation through cracking and delamination. This leads to the full loss of functional properties, including the improvement of corrosion resistance, as the corrosive environment gains direct access to the substrate.

The superior fatigue properties of the shot peened and cold sprayed specimens (Fig. 9) can be attributed to the improved coating adhesion rather than the shot peening effects of work hardening and compressive residual stress accumulation. In fact, both machining and shot peening led to compressive residual stresses with a similar magnitude, but different depths. While in the case of the machining process the residual stresses are generated by the contact force at the cutting tip and the affected depth is only about 0.05 mm, shot peening generates compressive residual stresses through the impact of hard particles, and the field reaches a depth of about 0.15 mm. As confirmed in [30], the cold spray process also accumulates compressive residual stress in the sub-surface material layers, as the spray particles impact the surface at an extremely high velocity. Thus, the final effect on the substrate is very similar to the shot peening process. However, the combination of big impact dimples (visible on the transversal sections in Fig. 8) and discontinuities between the substrate and the coating caused accelerated fatigue crack initiation in the as-machined and cold sprayed specimens.

6. Conclusions

Based on the obtained experimental results aimed at investigating the effect of shot peening applied prior to titanium cold spray coating, the following conclusions can be made:

- High velocity impacts of the cold spray titanium particles on the as-machined surface caused significant surface plastic deformation resulting in higher apparent roughness on the transversal section, when compared to the prior shot peened surface. The interface was also characterised by large voids on the coating/substrate interface.
- Titanium cold spray coating applied on the as-machined surface exhibited poor surface adhesion when subjected to cyclic mechanical loading. The fatigue crack initiated independently in the coating and in the substrate and ended with the total separation of the coating.
- When the surface layer is pre-hardened by shot peening followed by titanium cold spray deposition, the coating adhesion is significantly improved. The fatigue crack initiated beneath the coating and propagated through the substrate. No coating/substrate separation was observed near the fatigue crack initiation site.

Acknowledgements

This research was financially supported by project VEGA no. 1/0831/25 “Effect of hydrogen embrittlement on the mechanical properties and fatigue resistance of welded joints of high-strength structural steels”, a project of the European Union under the REFRESH - Research Excellence for Region Sustainability and High-tech Industries project number CZ.10.03.01/00/22_003/0000048 via the Operational Programme "Just Transition" and project no. 01.1.05.00/1.02.001/SUBB.MCKN.25.001 funded by the Ministry of Education and Science, Poland.

REFERENCES

- [1] Terrenos-Bedoya, A.; Negrin, I.; Payá-Zaforteza, I.; Yepes, V. Hybrid steel girders: Review, advantages and new horizons in research and applications, *Journal of Constructional Steel Research* **2023**, 207, 107976. <https://doi.org/10.1016/j.jcsr.2023.107976>
- [2] Bao, J.; Wu, P.; Zhang, J.; Zhang, P.; Bai, Y.; Yuan, T.; Zhang, M.; Ma, F.; Song, L.; Shi, H. Machine learning models for predicting the corrosion behavior of a plain carbon steel in simulated marine environment, *Journal of Industrial and Engineering Chemistry* **2025**. <https://doi.org/10.1016/j.jiec.2025.10.024>
- [3] Rakanta, E.; Zafeiropoulou, TH.; Batis, G. Corrosion protection of steel with DMEA-based organic inhibitor, *Construction and Building Materials* **2013**, 44, 507-513. <https://doi.org/10.1016/j.conbuildmat.2013.03.030>
- [4] Wang, D.; Li, W.; Liu, J.; Li, X.; Ling, T.; Chen, X.; Zhou, D.; Tan, B.; Guo, L. Green dual-adsorptive inhibitor from Tetradium ruticarpum extract for mitigating chloride-induced carbon steel corrosion in acidic environments, *Sustainable Materials and Technologies* **2025**. <https://doi.org/10.1016/j.susmat.2025.e01698>
- [5] Bae, G.; Xiong, Y.; Kumar, S.; Kang, K.; Lee, Ch. General aspects of interface bonding in kinetic sprayed coatings, *Acta Materialia* **2008**, 56 (17), 4858–4868. <https://doi.org/10.1016/j.actamat.2008.06.003>
- [6] Vandadi, M.; Bond, T.; Asumadu, K. T.; Kleman, D.; Rahbar, N.; Soboyejo, W. Effect of nanoscale surface oxide layers on the cold spray of commercially pure titanium and Ti–6Al–4V powders, *Computational Materials Science* **2025**, 246, 113454. <https://doi.org/10.1016/j.commatsci.2024.113454>
- [7] Cavaliere, P.; Silvello, A. Mechanical and microstructural behaviour of cold-sprayed titanium and nickel based coatings, *Journal of Thermal Spray Technology* **2015**, 24, 1506–1512. <https://doi.org/10.1007/s11666-015-0331-2>

- [8] Pohler, O. E. M. Unalloyed titanium for implants in bone surgery, *Injury* **2000**, 31 (4), D7–D13. [https://doi.org/10.1016/S0020-1383\(00\)80016-9](https://doi.org/10.1016/S0020-1383(00)80016-9)
- [9] Niinomi, M. Mechanical properties of biomedical titanium alloys, *Materials Science and Engineering: A* **1998**, 243 (1-2) 231–236. [https://doi.org/10.1016/S0921-5093\(97\)00806-X](https://doi.org/10.1016/S0921-5093(97)00806-X)
- [10] Boyer, R. R. An overview on the use of titanium in the aerospace industry, *Materials Science and Engineering: A* **1996**, 213 (1-2) 103–114. [https://doi.org/10.1016/0921-5093\(96\)10233-1](https://doi.org/10.1016/0921-5093(96)10233-1)
- [11] Leyens, C.; Peters, M. Titanium and titanium alloys: Fundamentals and applications, *Publisher Weinheim: Wiley-VCH* **2003**, 1st edition, ISBN:9783527305346, 513. <https://doi.org/10.1002/3527602119>
- [12] Weiss, I.; Semiatin, S. L. Thermomechanical processing of beta titanium alloys – an overview, *Materials Science and Engineering: A* **1998**, 243 (1-2), 46–65. [https://doi.org/10.1016/S0921-5093\(97\)00783-1](https://doi.org/10.1016/S0921-5093(97)00783-1)
- [13] Mohseni, E.; Zalnezhad, E.; Bushroa, A. R.; Hamouda, A. M.; Goh, B. T.; Yoon, G. H. Ti/TiN/HA coating on Ti–6Al–4V for biomedical applications, *Ceramics International* **2015**, 41 (10), 14447–14457. <https://doi.org/10.1016/j.ceramint.2015.07.081>
- [14] Celik, I.; Ural, A. G.; Aliyazici, M.; Cicek, D. Anodic coating of pure titanium: Structural and tribological effects of surface roughness diversity, *Results in Surfaces and Interfaces* **2025**, 18, 100449. <https://doi.org/10.1016/j.rsurfi.2025.100449>
- [15] Sirvent, P.; Garrido, M. Á.; Sharp, J.; Rainforth, W. M.; Poza, P. Improving the oscillating wear response of cold sprayed Ti–6Al–4V coatings through a heat treatment, *Surface and Coatings Technology* **2020**, 399, 126128. <https://doi.org/10.1016/j.surfcoat.2020.126128>
- [16] Jafarlou, D. M.; Ferguson, G.; Nardi, A.; Champagne, V.; Grosse, I. R. Cold spray deposition of pure titanium coating onto high strength substrate with ultra-high bond strength, *International Mechanical Engineering Congress and Exposition* **2019**, 7. <https://doi.org/10.1115/IMECE2019-11689>
- [17] Marrocco, T.; Hussain, T.; McCartney, D. G.; Shipway, P. H. Corrosion performance of laser post-treated cold sprayed titanium coatings, *Journal of Thermal Spray Technology* **2011**, 20, 909–917. <https://doi.org/10.1007/s11666-011-9637-x>
- [18] Stoltenhoff, T.; Borchers, C.; Gärtner, F.; Kreye, H. Microstructures and key properties of cold-sprayed and thermally sprayed copper coatings, *Surface and Coatings Technology* **2006**, 200 (16-17), 4947–4960. <https://doi.org/10.1016/j.surfcoat.2005.05.011>
- [19] Theimer, S.; Graunitz, M.; Schulze, M.; Gaertner, F.; Klassen, T. Optimization adhesion in cold spraying onto hard substrates: A case study for brass coatings, *Journal of Thermal Spray Technology* **2019**, 28, 124–134. <https://doi.org/10.1007/s11666-018-0821-0>
- [20] Kumar, S.; Bae, G.; Lee, C. Influence of substrate roughness on bonding mechanism in cold spray, *Surface and Coatings Technology* **2016**, 304, 592–605. <https://doi.org/10.1016/j.surfcoat.2016.07.082>
- [21] Singh, S.; Singh, H.; Chaudhary, S.; Buddu, R. K. Effect of substrate surface roughness on properties of cold-sprayed copper coatings on SS316L steel, *Surface and Coatings Technology* **2020**, 389, 125619. <https://doi.org/10.1016/j.surfcoat.2020.125619>
- [22] Nastic, A.; Vijay, M.; Tieu, A.; Rahmati, S.; Jodoin, B. Experimental and numerical study of the influence of substrate surface preparation on adhesion mechanisms of aluminum cold spray coatings on 300M steel substrates, *Journal of Thermal Spray Technology* **2017**, 26, 1461–1483. <https://doi.org/10.1007/s11666-017-0602-1>
- [23] Bruera, A.; Puddu, P.; Theimer, S.; Vidaller, V. M.; List, A.; Bolelli, G.; Gärtner, F.; Klassen, T.; Lusvardi, L. Adhesion of cold sprayed soft coatings: Effect of substrate roughness and hardness, *Surface and Coatings Technology* **2023**, 466, 129651. <https://doi.org/10.1016/j.surfcoat.2023.129651>
- [24] Samson, T.; MacDonald, D.; Fernández, R.; Jodoin, B. Effect of pulsed waterjet surface preparation on the adhesion strength of cold gas dynamic sprayed aluminum coatings, *Journal of Thermal Spray Technology* **2015**, 24, 984–993. <https://doi.org/10.1007/s11666-015-0261-z>
- [25] Tan, A. W. Y.; Sun, W.; Bhowmik, A.; Lek, J. Y.; Song, X.; Zhai, W.; Zheng, H.; Li, F.; Marinescu, I.; Dong, Z.; Liu, E. Effect of substrate surface roughness on microstructure and mechanical properties of cold-sprayed Ti6Al4V coatings on Ti6Al4V substrates, *Journal of Thermal Spray Technology* **2019**, 28, 1959–1973. <https://doi.org/10.1007/s11666-019-00926-5>
- [26] Kumar, A.; Singh, H.; Kant, R. Influence of substrate roughness and ceramic content on deposition characteristics of cold-sprayed Ti/TiO₂ deposits, *Metals and Materials International* **2023**, 29, 1669 – 1683. <https://doi.org/10.1007/s12540-022-01323-4>
- [27] Kommers, J. B.; Moore Hebert, F. The Fatigue of Metals, *Publisher – Legare Street Press* **2022**, 344, ISBN 978-1016608213

- [28] Yan, H.; Zhu, P.; Chen, Z.; Zhang, H.; Zhang, Y.; Zhang, Y. Effect of shot peening on the surface properties and wear behavior of heavy-duty-axle gear steels, *Journal of Materials Research and Technology* **2022**, 17, 22-32. <https://doi.org/10.1016/j.jmrt.2021.12.126>
- [29] Bond, T.; Sousa, B.; Rahbar, N.; Cote, D.; Tsaknopoulos, K.; Soboyejo, W. Fatigue and delamination of 6061 aluminum cold spray on a similar wrought substrate, *Materials Science and Engineering: A* **2024**, 913, 147024. <https://doi.org/10.1016/j.msea.2024.147024>
- [30] Moridi, A.; Hassani-Gangaraj, S. M.; Vezzú, S.; Trško, L.; Guagliano, M. Fatigue behaviour of cold spray coatings: The effect of conventional and severe shot peening as pre-/post-treatment, *Surface & Coatings Technology* **2015**, 283, 247–254. <https://doi.org/10.1016/j.surfcoat.2015.10.063>

Submitted: 18.6.2025

Accepted: 08.12.2025

Martin Vicen*
Faculty of Mechanical Engineering,
University of Žilina, Slovakia
Libor Trško
Research Centre, University of Žilina,
Žilina, Slovakia & VSB-TU Ostrava,
CPIT – Centre for Advanced Innovation
Technologies, Czech Republic
Otakar Bokůvka
Eva Nogová
Research Centre, University of Žilina,
Žilina, Slovakia
A. Góral
Institute of Metallurgy and Materials
Science, Polish Academy of Science,
Krakow, Poland
W. Żórawski
Faculty of Mechatronics and Mechanical
Engineering, Kielce University of
Technology, Kielce, Poland
*Corresponding author:
martin.vicen@fstroj.uniza.sk