Temperature and Stress Management in Cold Sprayed Deposits

Zahra Arabgol*, Sören Nielsen, Alexander List,
Levke Wiehler, Frank Gärtner, Thomas Klassen
Institute of Materials Technology
Helmut Schmidt University/
University of the Federal Armed Forces
Hamburg, Germany
*arabgolz@hsu-hh.de

Dhruvit Gabani*, Jens Gibmeier
Institute for Applied Materials (IAM-WK)
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
*dhruvit.gabani@kit.edu

***Abstract* – Material deposition in cold spraying occurs in solid state and thus avoids undesired effects of melting and solidification. However, residual stress conditions in cold sprayed coatings could limit possible part performance. The temperature distribution and thermal history of the cold sprayed components has significant influence on stress distribution and thus deposition and part quality.**

The present study investigates the effect of substrate material and nozzle traverse speed (as a secondary parameter) on effective temperatures and residual stress distributions of titanium-grade 1 deposits. The results demonstrate that substrate material properties and nozzle traverse speeds have significant influence on residual stresses of the cold spray deposit. It is understood that coefficient of thermal expansion (CTE) difference of the coating and substrate materials has significant effect on residual stress state. On the other hand, the residual stresses change from more compressive to more tensile state as the temperature of the components increases by decreasing the nozzle traverse speed. These findings indicate that thermal parameters affect residual stresses substantially. Thus, by adjusting the kinematic parameters and reducing maximum reached local temperatures within the part, more favorable stress states of the finished component can be obtained. The attained knowledge is essential for the development of high-quality deposits and the selection of the best strategies for repair and additive manufacturing applications.

Keywords – Cold spray, residual stress, kinematic parameters, thermal property, repair

I. INTRODUCTION

Cold spraying, also known as cold gas dynamic spraying, is a solid-state coating and additive manufacturing technique. In this process, micron-sized powder particles are accelerated to high velocities by an expanding gas stream in a converging diverging De-Laval type nozzle. The particles impact in the solid state onto the substrate at high velocity. Therefore, the formation of coatings occurs due to the kinetic energy of the particles. Extensive plastic deformation and related phenomena at the interfaces ensures bonding of the particles and allows for forming dense and internally well bonded coatings [1], [2]. Due to relatively low temperature in cold spraying, high oxide content, phase transformations, compositional changes and other problems associated with thermal spray methods are mostly alleviated [3], [4]. That makes cold spraying particularly suitable for spraying materials, which are sensitive to heat or oxidation such as Ti and its alloy [3]. With these characteristics, cold spraying proves to be a suitable technique for processing of functional coatings. In addition, it also enables part repair and additive manufacturing of bulk components.

Cold gas spraying can be used in many sectors, including the aerospace, automotive, transportation, metal processing, electronics, marine, and ceramics and glass manufacturing industries [5]. Due to advantages by low temperature processing, cold gas spraying is currently in the focus of interest for repair and additive manufacturing applications. For both, several studies investigated the deposit quality and the effect of kinematic and process parameters on the deposit qualities for different combinations of metallic materials [6], [7], [8], [9].

In all applications the integrity of the entire component should be ensured. As one of the factors that influence the quality of the deposit, residual stresses can affect the adhesion, wear, fatigue life and overall performance of the cold sprayed components [4]. Therefore, it is essential to gain a better knowledge about the sources of residual stresses and the parameters that change their magnitude and states.

Residual stresses in cold sprayed components can be divided into two categories: 1) Mechanical, mainly compressive stresses that are generated by peening effects upon particle impact and consequent plastic deformation. 2) Thermal mainly tensile stresses that are generated by the thermal mismatch of substrate and coating due to different coefficients of thermal expansion (CTE), rapid cooling of the particles after impact (quenching stress), and/or temperature gradients in the multi-pass deposition process [4], [10], [11].

There are some studies in the literature that examine the effect of substrate materials, process and kinematic parameters on the development of residual stresses in cold sprayed components. Their findings show that the coating - substrate material combinations as well as the process parameters and kinematics influence the final residual stress states by thermal and mechanical properties and reached temperature distributions within the component [11], [12], [13]. According to Suhonen et al. the generated stresses in cold sprayed coatings can be either compressive or tensile, dependent on (i) the density of particles and their deformation behaviour upon impact, and (ii) the CTEs of the sprayed material and the substrate [11]. Schmitt et al. showed that slowing down the robot traverse speed could shift the typical compressive residual stresses to tensile residual stresses for IN718 coatings on IN718 substrate [12]. Marzbanrad et al. have investigated the effect of substrate temperature and exposure time on residual stress formation in Al7075 coatings on AZ31B. They found that by controlling the heat input (nozzle speed), cooling rate (substrate heat transfer), and the number of colliding particles (feed rate), desirable tensile and/or compressive residual stress were produced in the substrate near the interface and at the coating surface. According to their results, the thermal mismatch between the Al7075 coating and AZ31B substrate caused tensile residual stress induced into the substrate [13].

However, there is no comprehensive study on residual stress evaluation in pure titanium deposits. Therefore, the present study investigates the effect of the substrate material and nozzle traverse speed (as kinematic parameter) on the residual stresses of titanium-grade 1 (Ti-Gr1) coatings and respectively obtained temperature developments over the components. The aim was to gain a deeper understanding about the sources and effective parameters on the magnitude and final state of residual stresses in titanium coatings. The findings should provide a guideline for tuning of residual stresses by adjusting the nozzle traverse speeds for using different coating - substrate combination.

There are different methods to measure residual stress, in this study the hole drilling method was used to analyse the residual stresses over the entire coating thickness [14], [15].

II. MATERIALS AND METHODS

Feedstock powder of titanium-grade 1 (99.7%) from Eckart TLS GmbH, Germany was cold sprayed onto flat substrates (70 × 50 × 3 mm^3). Titanium-grade 2 (Ti-Gr2), steel AISI304, and commercially pure copper (CP) were selected as substrate materials. Powder particles were almost spherical in shape and the particle sizes were in the range of 32-45 µm. Cold gas spraying was performed by using a system of type 5/11 from Impact Innovation GmbH, Germany. On each substrate, an area of 50 × 50 mm^2 was coated with Ti-Gr1 in thickness of about 1 mm. The process parameters and the materials specific data considered in this study are shown in Table I and II, respectively. In order to avoid additional stresses, the substrates were only cleaned and not pretreated prior to the coating process. Different heat input and thus temperatures during the spray process were attained by variation of the kinematic parameters via applying different nozzle traverse speed of 125 mm/s, 250 mm/s and 500 mm/s, respectively. To reach the same coating thickness of about 1 mm in all cases, the number of layers differ for each traverse speed (see Table II).

TABLE I: COLD SPRAY PROCESS PARAMETERS

Gas temperature (°C)	*Gas pressure (bar)*	*Line distance (mm)*	*Standoff distance (mm)*
1100	45	2	40

TABLE III: MATERIAL PROPERTIES USED IN THIS STUDY (MATWEB.COM)

Material	*Conductivity (W/mk)*	*Thermal Expansion (µm/m-°C)*	*Density (kg/m^3)*	*Tensile Strength (MPa)*
Titanium-Gr 1	16	9.7	4500	240
Titanium-Gr 2	16.4	9.7	4500	344
CP copper	385	20.2	8900	260
Steel- AISI304	16	18.9	8000	564

TABLE III: INVESTIGATED VARIABLES

Substrate materials	Titanium Grade 2		
	Steel AISI304		
	CP copper		
Nozzle traverse speed (mm/s)	125	250	500
Number of layers	2	4	8

The experimental analyses concerned thermal and residual stress measurements. The thermal history of the components over the duration of the coating process was measured by inserting a thermocouple into a 1 mm diameter hole, drilled into the substrate from backside to a depth of about 2 mm, as shown in Figure 1 [4]. Residual stresses through the depth of the coating was measured by incremental hole-drilling method (ASTM E837 standard), by introducing a blind hole in certain number of drilling steps (increments) and recording the strain relaxation after each step. The recorded strain is then converted into stress using a specific evaluation method [15]. Instead of standard centre hole-drilling, for present experiments an orbital drilling technique was employed [16]. An in-house hole-drilling device at the Karlsruhe institute of technology (KIT), which has a high-speed air turbine facilitated by an orbital motion, was used for incremental hole-drilling.

FIGURES 1: PLACEMENT OF THERMOCOUPLE FROM THE BACKSIDE OF THE SUBSTRATE. A DEPTH OF APPROX. 2 MM, APPROXIMATELY REFERS TO A DISTANCE OF 1MM TO THE SUBSTRATE SURFACE

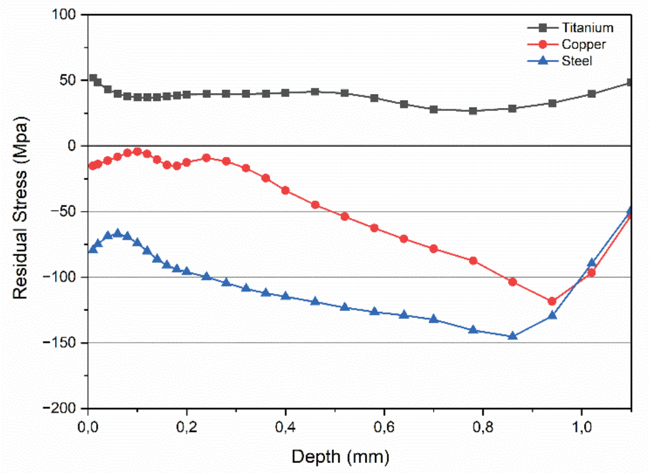
III. RESULTS AND DISCUSSION

A. *Effect of Substrate Material on Residual Stress*

Figure 2 displays the residual stresses throughout the thickness of Ti-Gr1 coatings on the different substrate materials according to Table II by using a nozzle traverse speed of 500 mm/s. Covering a depth of approximately 1.1 mm, the graphs show that the residual stresses are tensile in case of the titanium substrate and compressive in case of the steel and copper substrates.

The behaviour of residual stress of Ti-Gr1 coatings on the steel and copper substrate, could be explained by different coefficient of thermal expansion (CTE) between coating and substrate materials. The difference in CTE of the coating and substrate materials induces thermal stresses due to thermal misfit strain [4], [10], [11]. While the CTE of the substrate is greater than that of the coating, it means that the substrate expands and contracts more than the coating during the heating and cooling phases, respectively. This results in major thermal misfit strain and causes compressive thermal stresses dominating the ultimate residual stress state.

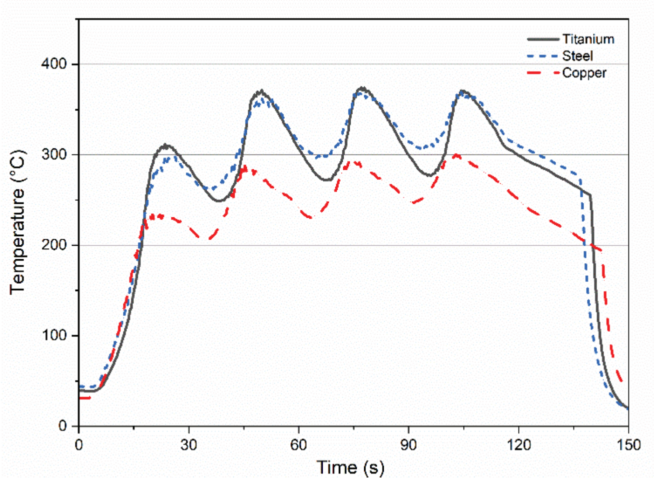
Despite the almost similar CTE, the coating stress levels on steel and copper substrates are different, which may be attributed to the mechanical and thermal properties of steel and copper. The lower thermal conductivity of the steel can cause a steeper temperature gradient. On the other hand, the lower stiffness of copper may cause more bending of the coating-substrate bimetal than in case of the stiffer steel substrate. As a result, more stresses could be released. Associated different stress states during deposition can lead to higher compressive residual stresses in the overall Ti-Gr1 coating (according to Figure 2).



FIGURES 2: RESIDUAL STRESS THROUGHOUT THE THICKNESS OF TI GRADE 1 COATINGS ON DIFFERENT SUBSTRATE MATERIALS AS PROCESSED WITH A NOZZLE TRAVERSE SPEED OF 500 MM/S

In the case of the Ti-Gr1 coating on Ti-Gr2 substrate, the absence of CTE differences between the coating and the substrate materials avoids contributions from thermal misfit strains onto the stress development. Despite the expected compressive stress due to the peening effect of particles impact, the stress state in this case is tensile. This can be explained by temperature gradients over coating and substrate, and their history over the duration of the spray process. According to Figure 3, the overall temperature in case of the titanium substrate is higher than that by using a copper substrate. The lower thermal conductivity of Ti as compared to Cu restricts fast heat diffusion and keeps the coating itself and the substrate volumes close to the interface at higher temperatures. Less steep temperature gradients may be the reason for the tensile residual stresses in the case of the titanium substrate that even overcompensate the peening effect by the impacting particles. According to Boruah et al., the residual stresses in cold gas sprayed Ti-6Al-4V coatings on Ti-6Al-4V substrate deposited with similar process parameters (1100 °C gas temperature and 50 bar gas pressure) were also found to be tensile in the coatings [17].

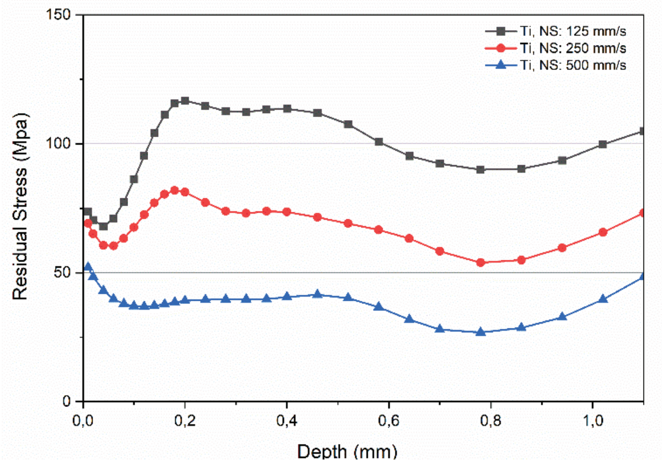
Apart from overall stress states, also differences over the depth within the coatings can be distinguished. The residual stresses of the Ti-Gr1 coating on copper and steel substrates show a gradient and get more compressive near the interface between coating and substrate. This could contribute to peening effects by particle impact being less compensated by tensile stresses due to thermal effects. During build-up of the first layers, the cold substrate as effective heat sink ensures fast heat extraction and thus lower coating temperatures.



FIGURES 3: TEMPERATURE DEVELOPMENT WITHIN THE SUBSTRATES AS OBTAINED BY APPLYING A NOZZLE TRAVERSE SPEED OF 500 MM/S DURING SPRAYING

B. *Effect of Nozzle Traverse Speed on Residual Stresses*

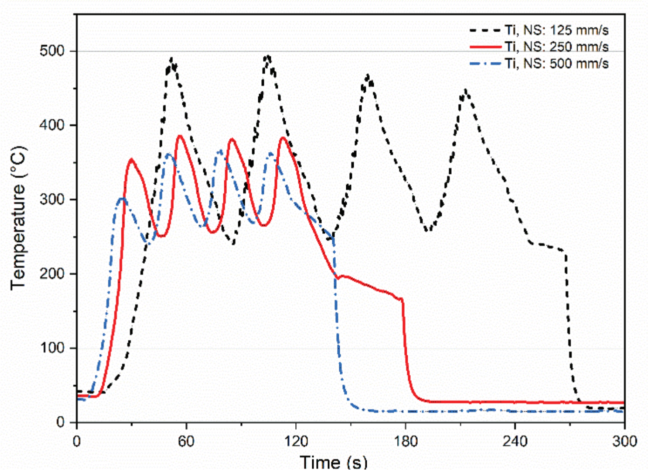
Figure 4 shows the effect of nozzle traverse speed on the residual stresses of Ti-Gr1 coating on Ti-Gr2 substrate. As the nozzle traverse speed decreases, the residual stress in the coating tends to more tensile states. A nozzle traverse speed of 500 mm/s causes the lowest tensile stress and nozzle traverse speed of 125 mm/s causes the highest tensile stress. These results correlate to the temperatures reached during deposition.



FIGURES 4: RESIDUAL STRESS THROUGHOUT THICKNESS OF TI GRADE 1 COATING ON TI GRADE 2 SUBSTRATE BY APPLYING NOZZLE TRAVERSE SPEEDS OF 125 MM/S, 250 MM/S, AND 500 MM/S

The thermal history of the parts during deposition (Figure 5) show that by decreasing the nozzle traverse speed, the temperature in the substrate close underneath the coating increases with decreasing traverse speeds. That is due to a longer duration of local heating on the component (increasing the thermal input). This indicates that a lower traverse speed increases local temperature and enhances the contribution of quenching effect by rapid cooling of the particles after impact and shifts the residual stress distributions towards a more tensile mode. This is consistent with reports from Schmitt et al. for NI718 coatings [12] and Marzbanrad et al. for Al7075 coatings [13].

According to this finding, it is important to adjust and find the optimum nozzle traverse speed to achieve the best coating quality in terms of residual stress states.



FIGURES 5: THERMAL HISTORY OF TI-GR2 SUBSTRATES BY APPLYING NOZZLE TRAVERSE SPEEDS OF 125 MM/S, 250 MM/S, AND 500 MM/S

C. General

In this study, the effect of substrate materials and nozzle traverse speed were investigated. It can be assumed that impacts in the solid state at first instance contribute to compressive peening stresses. These peening stresses are to different extent superimposed by tensile thermal stresses. The heat input per unit area in combination with thermal and heat transfer parameters determines the effective surface temperature and temperature gradients during deposition and in consequence the thermal history and stress development within the component during cooling. Hence, having more knowledge about thermal related parameters and effective kinematic parameters on temperature and resulting stress distributions within the cold sprayed components is crucial for reaching optimum part performance.

The levels of thermal stresses depend on substrate material types and applied kinematics. The choice of substrate material by CTE mismatch and different temperature gradients influence the contributions by thermal tensile stresses. Tensile contributions scale with temperatures attained just underneath the coatings within the substrate.

Apart from substrate material, also the choice of kinematics determines coating stress states following similar rules. Higher locally reached temperatures close to the interface by lower travers speeds results in higher contributions by tensile stresses. Thus, these primary investigations allow supplying a first guideline to tune coating stresses by thermal management as attainable by kinematics during deposition.

IV. SUMMARY AND CONCLUSION

This study investigates the residual stresses of cold sprayed Ti-Gr1 coatings and respective influences by substrate materials and local heat input by different nozzle traverse speeds as a kinematic parameter. The main conclusion of this study is summarized as follows:

- Solid state impacts by cold spraying in first instance cause compressive stresses by peening effects. The overall residual stresses are determined by the superposition of these compressive stresses with tensile stresses due to local temperature rises under the spray jets and respective temperature gradients.
- The tensile stresses can overcompensate the compressive stresses and thus determine the overall stress states.
- The type of substrate material determines tensile stress levels by the mismatch of thermal expansion coefficients with respect to the coating material and the thermal effusivity. A higher thermal effusivity and thus more efficient heat extraction reduces coating and surface temperatures and thus thermal stresses.
- Tensile stress contributions depend on applied kinematics during deposition. A higher nozzle travers speed leads to a shorter heating duration and thus lower locally reached temperatures during one pass. The lower coating temperatures result in reduced tensile residual stresses.
- The tensile stress contributions and thus the overall coating stress states can be influenced by thermal management during deposition. Thus, robot kinematics proves as key parameter to adjust the needed coating and part stress levels.

ACKNOWLEDGEMENT

The authors acknowledge the financial support in the frame of the project "CORE – Computerized Refurbishment" funded by dtec.bw - Digitalization and Technology Research Center of the Bundeswehr. Digitalization and Technology Research Center of the Bundeswehr is a scientific centre jointly supported by the Universities of the Federal Armed Forces in Hamburg and Munich and is part of the German government's economic stimulus program to overcome the COVID-19 crisis. It is subject to academic self-administration. The funds within dtec.bw for both universities of the Federal Armed Forces finance research projects and projects for knowledge and technology transfer. dtec.bw is funded by the European Union – NextGenerationEU.

REFERENCES

[1] H. Assadi, F. Gärtner, T. Stoltenhoff, and H. Kreye, "Bonding Mechanism in Cold Gas Spraying", *Acta Materialia*, vol. 51, pp. 4379– 4394, 2003.

[2] T. Schmidt, F. Gärtner, H. Assadi, and H. Kreye, "Development of a generalized parameter window for cold spray deposition." *Acta Materialia*, vol. 54(3), pp. 729-742, 2006.

[3] T. Stoltenhoff, H. Kreye, and H.J. Richter, "An analysis of the cold spray process and its coatings", *Journal of Thermal Spray Technology*, vol. 11(4), pp. 542-550, 2002.

[4] Z. Arabgol, H. Assadi, T. Schmidt, F. Gärtner, and T. Klassen, "Analysis of thermal history and residual stress in cold sprayed coatings", *Journal of Thermal Spray Technology*, vol. 23, pp. 84-90, 2014

[5] "Cold spray coatings, recent trends and future perspective", *Springer International Publishing AG*, pp 3-24, 2018.

[6] S. Pathak and G. C. Saha, " Development of sustainable cold spray, coatings and 3D additive manufacturing components for repair/manufacturing applications: A Critical Review", *Coatings*, vol. 7(8)122. 2017.

[7] F. Lang, J-C. Schmitt, S. Cabeza, T. Pirling, J. Fiebig, R. Vassen, and J. Gibmeier, "IN718 cold gas repair spray of large cavities-microstructure and residual stresses", *Proceedings of the 10th International Symposium on Superalloy 718 and Derivatives*, pp. 739-753, 2023.

[8] S. Yin, P. Cavaliere, B. Aldwell, R. Jenkins, H. Liao, W. Li, and R. Lupoi, “Cold spray additive manufacturing and repair: Fundamentals and applications,” *Additive Manufacturing*, vol. 21, pp. 628–650, 2018.

[9] M. Faccoli, G. Cornacchia, D. Maestrini, G.P. Marconi, and R. Roberti, "Cold spray repair of martensitic stainless steel components", *Journal of Thermal Spray Technology*, vol. 23 (8), pp. 1270-1280, 2014.

[10] D. Boruah, X. Zhang, and M. Doré, "Theoretical prediction of residual stresses induced by cold spray with experimental validation", *Multidiscipline Modeling in Materials and Structures*, ISSN: 1573-6105, 2019.

[11] T. Suhonen, T. Varis, S. Dosta, M. Torrell, and J.M. Guilemany, " Residual stress development in cold sprayed Al, Cu and Ti coatings", *Acta Materialia*, vol 61, pp. 6329–6337, 2013.

[12] J. Schmitt, J. Fiebig, S. Schrüfer, O. Guillon, and R. Vaßen, "Adjusting residual stresses during cold spray deposition of IN718", Journal of Thermal Spray Technology, vol 33, pp. 210-220, 2024.

[13] B. Marzbanrad , E. Toyserkani , and H. Jahed, "Customization of residual stress induced in cold spray printing", *Journal of Materials Processing Technology*, vol. 289, 116928, 2021.

[14] Y.Y. Santana, J.G. La Barbera-Sosa, M.H. Staia, J. Lesage, E.S. Puchi-Cabrera, D. Chicot, and E. Bemporad, "Measurement of residual stress in thermal spray coatings by the incremental hole drilling method, *Surface & Coatings Techno*logy, vol. 201, pp. 2090-2098, 2006.

[15] E. Obelode and J. Gibmeier, "Residual stress analysis on thick film systems by the incremental hole-drilling method - Simulation and experimental results", *Experimental Mechanics*, vol. 53, pp. 965-976, 2013.

[16] G. S. Schajer and P. S. Whitehead, "Hole drilling and ring coring, *Practical Residual Stress Measurement Methods*, chapter 2, 2013.

[17] Boruah1, B. Ahmad, T. L. Lee, S. Kabra, A. Khadar Syed, P. McNutt, M. Doré, and X. Zhang, "Evaluation of residual stresses induced by cold spraying of Ti-6Al-4V on Ti-6Al-4V substrates", *Surface and Coatings Technology*, vol. 374, , pp. 591-602, 2019.