POSSIBILITIES OF CONTROLLING THE DEPTH OF REMELTING DURING LASER REMELTING OF THERMALLY SPRAYED COATINGS BY MEANS OF INFRARED THERMOGRAPHY

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Abstract

Laser remelting of thermally sprayed coatings is a promising possibility how to improve their functional properties. However, it requires precise control of processing parameters to achieve desired depth of remelting. In this study, the near-infrared (NIR) camera is used to measure the achieved depth of remelting during diode laser remelting of HVOF sprayed coatings. Possibilities how to evaluate the temperature field in the melting area are presented. The width of melting pool is calculated and it shows high correlation with achieved depth of remelting. The study shows that the NIR measurement can be used for controlling the depth of remelting during a laser remelting of coatings.

Keywords: Laser remelting, HVOF coatings, heat post-treatment, infrared diagnostic

1. INTRODUCTION

The High Velocity Oxygen Fuel (HVOF) spraying technology is widely used for the deposition of protective coatings with high wear, corrosion and temperature resistance. However, a typical lamellar microstructure of thermally sprayed coatings contains some imperfections such as pores, oxides and unmelted particles that can limit the functional properties of the created coating [1, 2]. The microstructure of the coatings and their functional properties can be enhanced by subsequent post-treatment, such is remelting by high power lasers [3-6]. However, the precise control of the remelting parameters is crucial, as the depth of the remelting play important role - the coatings remelted only partially can have significantly better functional properties than fully remelted coating [7].

Therefore, it would be beneficial to include some means of controlling of the remelting process. In similar laser applications, such as laser hardening [8-10] or laser cladding [11-13], in situ measurement using infrared detectors is often used to control the laser process. The possibility of using of NIR (near-infrared) camera to controlling the depth of remelting was already published [14].

In this paper, the more possibilities of IR measuring of remelting process and its evaluations are described. The correlation with achieved depth of remelting is presented and the merits and flaws of presented methods are discussed.

2. EXPERIMENTAL PROCEDURE

2.1. The remelting process

The HVOF coating was deposited onto a carbon steel. The FST 484.074 Stellite 6 Co-based alloy feedstock powder with the nominal composition 28%Cr, 5%W, 1.2%C, 1%Si, Co-rest; gas atomized, the particle size range 20-53 µm, was used for spraying by the HP/HVOF TAFA JP5000 spraying gun at Výzkumný a zkušební ústav Plzeň s.r.o. (Research and Testing Institute Plzeň). Three samples with different combinations of substrate and coating thickness were used: **A** (S10/C0.4); **B** (S20/C0.4); **C** (S20/C1), where the Sx/Cy mark the sample dimensions: x - the **S**ubstrate thickness (mm), y - the **C**oating thickness (mm).

HVOF sprayed samples were then laser remelted by the High Power Direct Diode (HPDD) laser Coherent HighLight ISL-4000L with spot dimensions 12 × 1 mm and maximal power 4.3 kW. The laser emits at the wavelength 808 ± 10 nm. Processing parameters were based on previous experiments. The laser power was kept constant (P = 1070 W) and the process speed (S) was varied in the range from 40 to 12.5 cm/min (6.67 to 2.08 mm/s) to change the radiant fluence (energy delivered to the surface) and achieve a different depth of remelting (the highest speed for a shallow remelting, the slowest for a full remelting of the coating with the thickness 0.4 mm). To decrease the level of internal stresses, responsible for samples deformation and cracks occurrence in the coating, the substrate preheating to temperature 350 °C was applied.

Cross-sections of remelted samples (perpendicular to the direction of processing) were ground and polished by automatic Leco grinding and polishing equipment. The depth of remelting was measured by a digital optical 3D microscope Hirox KH7700; it was averaged for 5 measurements.

2.2. The measurement by two LWIR cameras

In the first method, the remelting process was measured by two LWIR (long wavelength infrared) cameras. One, FLIR A615, was mounted directly on laser head and thus was moving simultaneously with a laser spot. The second one, VarioCAM hr head by Infratec, was static and recorded the whole treated sample. Both cameras have similar properties: temperature range -40 - 2000 °C, uncooled bolometric detector with spectral range 7.5 - 14 μm and resolution 640 × 480 px. The sequences were recorded with frequency 10 Hz. The emissivity necessary for temperature assessment was evaluated comparing the untreated and treated areas of the sample at the same temperature as an area of the sample treated with reference color of known emissivity.

The evaluations of measured data include assessment of average and maximal temperatures in the area of the laser beam interaction with material and its progress in time. Next, from the temperature progress for determined spots in the laser track were exported (from the record of the static camera). From this temperature profiles, the time of heating from minimal to maximal temperature T_{max} (marked as Δt_{heat}) and time of cooling from T_{max} to reference temperature T_{ref} = 600°C and 400 °C (marked as $\Delta t_{cool}(ref)$) was calculated.

2.3. Measurement using NIR camera

Subsequently, the remelting process was recorded by the Near-infrared (NIR) camera MICRON MCS640 (LumaSense), with a temperature range 800-3000 °C The telescopic optics (f = 75 mm, 3.5° x 2.6° FOV) was used. The spectral range of the uncooled silicon detector with resolution 640 × 480 pixels is 780-1080 nm. The camera was mounted directly on the laser.

Two spectral filters by Thorlabs (FEL0850: Longpass Filter, the Cut-off wavelength 850 nm; FES1000: Shortpass Filter, the Cut-off wavelength 1000 nm) were used to cut off the laser source radiation (λ = 808 nm) to protect the detector of the camera.

The temperature measurement in this NIR spectral range is more independent of the surface emissivity than in the case of using long-wavelength infrared (LWIR) cameras and thus provides a higher accuracy [15]. The emissivity of metals and coatings is higher in the NIR than in the LWIR range and it increases with an increasing temperature. Therefore, the emissivity was set to 1 during our measurement. Moreover, a change in the emissivity from 1 to 0.9 at the temperature 1500 °C results in an error of 23 °C (1.3% for values in K) and thus is not very significant.

Data from the IR measurement were evaluated with the following advancement: First, the temperature profile for three lines across the melting zone was exported at 10 equivalently distant time points for each track (with the given process speed). The width of the melting pool (marked as d_{ref}) was calculated from the number of pixels with a temperature higher than the reference temperature T_{ref}. For the reference temperature, following values were considered: 1000 °C - melt pool and HAZ (Heat Affected Zone); 1287°C, 1410 °C - lower and upper temperature of Stellite melting range. The resolution 25.4 px/mm was determined from the dimensions of the laser spot.

3. RESULTS AND DISSCUSION

3.1. The evaluated temperatures

In the **Figure 1A**), the measured temperatures from laser beam interaction area during one track are presented. It can be seen, than the average temperature in the area does not correspond to the melting range of Stellite (1285 - 1410°C). The temperature is averaged over a larger area than from melting pool and thus the temperature is lower. The maximal temperature is much higher and there is a lot of noise, as only one spot with max temperature in the area is measured and it can be highly unstable. Also higher temperatures are determined with high error, as the assessment of emissivity was for low temperatures. The temperature determination during measurement in LWIR spectral range is highly sensitive to correct values of emissivity.

In the **Figure 1B**), the averaged values (in time) for individual tracks of these average and max area temperatures are presented. In addition, there is the average value of the maximal temperature measured by second static camera varioCAM. This value should correspond to the average value of (max AOI2). But thanks to high errors in measurement due to incorrect emissivity values it does not correspond. Furthermore, the temperature for the individual track does not have clear progress.

From these reasons it was concluded, that temperature evaluation is not suitable for controlling of the depth of remelting.

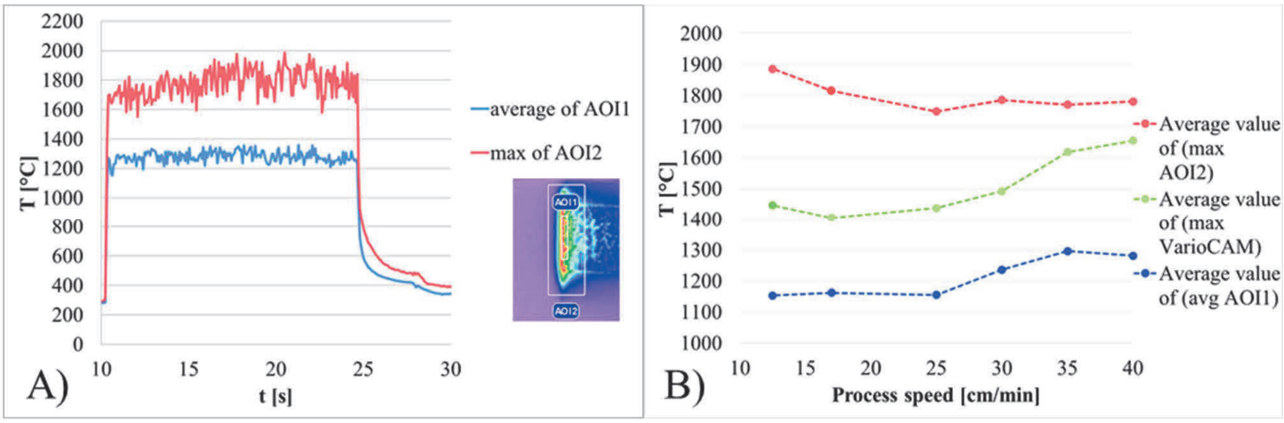

Figure 1 A) The evaluated temperatures in melting area during one track;
B) average values for individual tracks

3.2. The heating and cooling rate

The calculation of heating and cooling times partially overcome the problem of high errors in temperature determination due to emissivity. As only the time when the maximal temperature in the spot was reached and the precise value is not necessary. Nevertheless, it is still necessary to determinate reference temperature for calculation of cooling times. In **Figure 2A**), the values of heating and cooling times for individual tracks are displayed. As it can be seen, the times are decreasing with increasing process speed. In **Figure 1B** the dependence of reached depth of remelting on time of cooling Δt_{heat}(600°C) is presented. As it can be seen, the logarithmical correlation of the dependence have a high coefficient of determination ($R^2 = 0.994$), it marks high correspondence with original data.

The flaws of this method are that it still partially depends on temperature determination and thus it is dependent on right emissivity evaluation. The calculation of time of cooling is limited with the frequency of sequence recording and with high frequency, a lot of data has to be recorded. More, the evaluation is made from temperature evaluation of specific points in the sample and thus cannot be made automatically in laser spot interaction area.

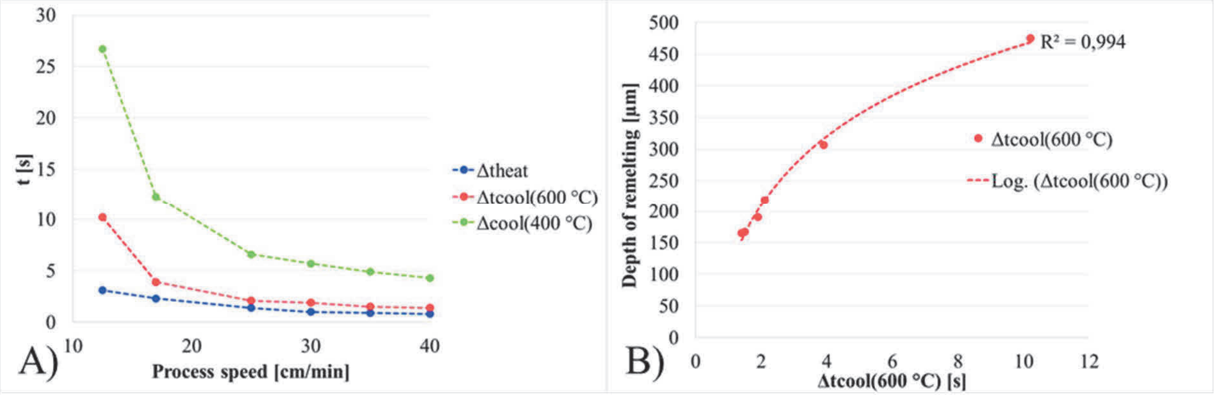

Figure 2 A) Cooling and heating rates for individual tracks;
B) Dependence of the depth of remelting on the cooling rate

3.3. The width of melting pool

Due to measuring in NIR spectral range, this method overcomes the problems of high errors in temperature assessment due to emissivity. More, the method of calculation further decreases the influence of right temperature determination, as the dimension of the area with a higher temperature than reference is calculated and the temperature itself is negligible. The exponential correlation of the dependence of the depth of remelting on the width of melting pool $d_{1000°C}$ and $d_{1287°C}$ for sample **A** (S10/C0.4) is presented in **Figure 3A**). The high coefficient of determination for both reference temperature marks high correspondence with original data.

To verify the applicability of this method, the sample with different coating and substrate thickness were remelted. The resulting exponential correlation of the dependence of the depth of remelting on the width of melting pool $d_{1000°C}$ for samples **A** (S10/C0.4), **B** (S20/C0.4) and **C** (S20/C1) combined is presented on **Figure 3B**). The correlation shows still very high coefficient of determination (R^2 = 0.994). It marks, that this method of non-contact IR measurement of the width of melting pool is very suitable for assessment of the reached depth of remelting during laser remelting. The method is independent of the dimension of a remelted sample, on its substrate and coating thicknesses.

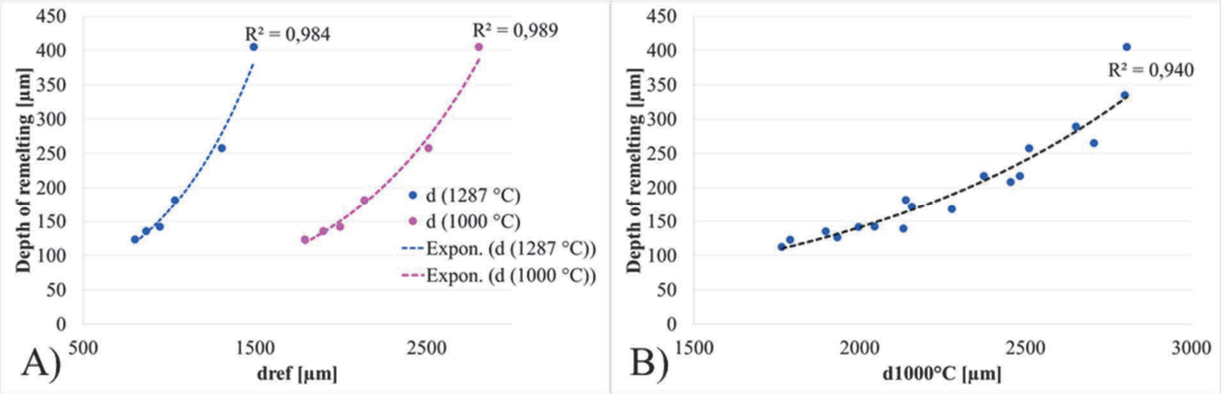

Figure 3 Dependence of depth of remelting on width of meting pool: **A)** Sample A and reference temperature 1287 °C and 1000 °C; **B)** All samples combined and reference temperature 1000 °C

4. CONCLUSION

The possible methods of using infrared cameras to measuring the laser remelting of HVOF coating were presented. By using cameras measuring in LWIR spectral range, the evaluation of temperature is highly dependent on the correct emissivity value. The direct measurement of temperature in laser spot is not suitable for measuring the depth of remelting. The calculation of cooling rate is more suitable and the shows high correspondence with the reached depth of remelting. However, using NIR camera and calculating the width of melting pool was shown as even more suitable for controlling the depth of remelting. This method is highly independent on the emissivity of the treated surface. The exponential correlation of the dependence of the depth of the remelting on the width of melting pool shows very high correspondence, even when remelting samples with different substrate/coating thickness.

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REFERENCES

[1] D.E. CRAWMER. *Handbook of Thermal Spray Technology*. ASM International, Materials Park, OH, USA, 2004.

[2] PLANCHE, M.P. P, LIAO, H., NORMAND, B., CODDET, C., B., Normand and CODDET, C. Relationships between NiCrBSi particle characteristics and corresponding coating properties using different thermal spraying processes. *Surface and Coatings Technology*. 2005. Vol. 200, no. 7, p. 2465-2473. DOI 10.1016/j.surfcoat.2004.08.224.

[3] SERRES, N, HLAWKA, F, COSTIL, S, LANGLADE, C and MACHI, F. Microstructure of Metallic NiCrBSi Coatings manufactured via Hybrid Plasma Spray and In Situ Laser Remelting Process. *Journal of Thermal Spray Technology*. 2011. Vol. 20, p. 336-343.

[4] TUOMINEN, J, VUORISTO MÄNTYLÄ, T., P, VIHINEN, J and ANDERSSON, P H. Corrosion behavior of HVOF-sprayed and Nd-YAG laser remelted high-chromium, nicel-chromium coatings. *Journal of Thermal Spray Technology*. 2011. Vol. 11, p. 233-243.

[5] LUGSCHEIDER, E., HOFMANN, D. and NICOLL, A. R. Optimalization of Spraying Process and Laser Treatment of CoNiCrAlY. *Journal of Thermal Spray Technology*. 1992. Vol. 1, p. 239-247.

[6] GONZÁLEZ, R., CADENAS, M., FERNÁNDEZ, R., CORTIZO, J.L. and RODRÍGUEZ, E. Wear behaviour of flame sprayed NiCrBSi coating remelted by flame or by laser. *Wear*. 2007. Vol. 262, no. 3, p. 301-307. DOI 10.1016/j.wear.2006.05.009.

[7] HOUDKOVÁ, Šárka, PALA, Zdenek, SMAZALOVÁ, Eva, VOSTŘÁK, Marek and ČESÁNEK, Zdeněk. Microstructure and sliding wear properties of HVOF sprayed, laser remelted and laser clad Stellite 6 coatings. *Surface and Coatings Technology*. 2016. DOI 10.1016/j.surfcoat.2016.09.012.

[8] ATTIA, H., TAVAKOLI, S., VARGAS, R. and THOMSON, V. Laser-assisted high-speed finish turning of superalloy Inconel 718 under dry conditions. *CIRP Annals - Manufacturing Technology* [online]. 2010. Vol. 59, no. 1, p. 83-88. DOI 10.1016/j.cirp.2010.03.093.

[9] HÖMBERG, Dietmar and WEISS, Wolf. PID Control of Laser Surface Hardening of Steel. . 2006. Vol. 14, no. 5, p. 896-904.

[10] SANTHANAKRISHNAN, S and KOVACEVIC, R. Hardness prediction in multi-pass direct diode laser heat treatment by on-line surface temperature monitoring. *Journal of Materials Processing Technology,*. 2012. Vol. 212, p. 2261-2271.

[11] PAVLOV, M, NOVICHENKO, D and DOUBENSKAIA, M. Optical Diagnostics of Deposition of Metal Matrix Composites by Laser Cladding. *Physics Procedia* [online]. 2011. Vol. 12, p. 674-682. DOI 10.1016/j.phpro.2011.03.084.

[12] SMUROV, I, DOUBENSKAIA, M and ZAITSEV, A. Technology Comprehensive analysis of laser cladding by means of optical diagnostics and numerical simulation. *Surface & Coatings Technology* [online]. 2013. Vol. 220, p. 112-121. DOI 10.1016/j.surfcoat.2012.10.053.

[13] DOUBENSKAIA, M, PAVLOV, M, GRIGORIEV, S and SMUROV, I. Definition of brightness temperature and restoration of true temperature in laser cladding using infrared camera. *Surface & Coatings Technology* [online]. 2013. Vol. 220, p. 244-247. DOI 10.1016/j.surfcoat.2012.10.044.

[14] VOSTŘÁK, Marek, TESAŘ, Jiří, HOUDKOVÁ, Šárka, SMAZALOVÁ, Eva and HRUŠKA, Matěj. Diagnostic of laser remelting of HVOF sprayed Stellite coatings using an infrared camera. *Surface and Coatings Technology* [online]. January 2017. [Accessed 8 March 2017]. DOI 10.1016/j.surfcoat.2016.12.118.

[15] TESAŘ, J, MARTAN, J and SKALA, J. The influence of emissivity on measured temperature in dependence on spectral range of IR camera detector and its approximate calculation. In : *Quantitative Infrared Thermography conference, QIRT 2016,*. Gdansk, 2016. p. 89-99.