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Abstract. This paper is devoted to the assurance of higher durability of hard coatings by using irregular method of laser cladding (LC). The purpose of this study was to demonstrate that by producing of keyhole mode LC coatings enables to create functionally graded structure in interface. This can contribute to decrease the gradient of trough-depth residual stresses of the coating-substrate system formed by dissimilar steels. Experimental work was carried out using precise LC system, which consists of industrial robot (KUKA) and 1kW Yb-fiber laser (IPG Laser). Experimental coatings were created on cold work tool steel substrate AISI D2 using high-speed steel (HSS) powder AISI M2. The properties of coatings produced by two different methods have been evaluated in the course of a comparative analysis by examination of morphology of transverse cross-sections, elemental composition, microhardness distribution inside coatings and tribological tests. Results showed that coating with keyhole mode in penetration had lower hardness due to a larger amount of dilution however the smooth transition of properties in the interface was obtained. Despite the significant difference in hardness both coatings demonstrated very similar tribological behaviour.

1. Introduction
The main resources for strength increasing of structural materials have almost been exhausted. For this reason, coating creation on the surfaces of machinery parts has become a worldwide trend, which is a naturally determined solution of this quite a serious problem. The capabilities of homogeneous single-component coatings are at the moment also close to exhaustion, therefore, in order to obtain the possibility of combining various physically-mechanical properties of coatings while in operation, the researchers are following the line of creating composite coatings that nowadays are being actively developed [1]. However composite materials have physical and mechanical properties which differ a lot from those of the base material. Naturally residual stresses appear on the interface of the coating and the substrate, which significantly impair the quality of the coatings. To solve this problem, creation of gradient layers could help, which would have high content of hardening elements on the surface to meet functional requirements, and also high content of the metal component close the boundary with the substrate, to approximate the properties of the coating and the base material. This is a good solution when creating hardening coatings on various base materials [2]. Such coatings are called functionally graded (FGC). In general, change of the FGC properties is connected with a
corresponding variation of the chemical composition and physical structure of the material. For achieving this layered coatings with varying compositions of each individual layer can be used. The gradient of properties towards the volume of material can be regulated, besides, by varying degree of filling, and towards the surface, by changing for example degree of modification [3].

Laser cladding (LC) is a progressive technology of surface engineering, which is increasingly used to improve mechanical and tribological properties of metallic components by creating functional coatings herewith providing a combination of strong metallurgical bond with minimal thermal distortion of substrate [4]. As a result of many advantages in comparison to thermal spraying and conventional welding processes LC is successfully applied for hardfacing, refurbishment and repair of high value machine components and tools (turbines, dies, punches, press molds etc.) and which also finds application in the additive manufacturing industry [5]. LC allows applying of single beads and layers of coatings of small dimensions, which cross-sections are comparable to the size of the laser spot on the cladded surface. The intermixing of the material of the cladded beads with each other and with the substrate material can be well controlled and kept to minimum. Adhesion strength of deposited clad beads is excellent, the range of technological parameters of laser cladding is quite large and respectively the coating application regimes can be chosen quite freely [6]. The indicated properties of laser cladding point at the possibility of creating FGC with its help, as far as coatings can be created from single beads and layers of beads of various compositions [7]. As creation of the FGC implies multitasking, the question of laser cladding method usage for its creation both in means of coating volume as well as of its surface is becoming especially actual nowadays. This would help to solve effectively the problems of both the strength of the coating-substrate system and the insuring of high physically-mechanical properties of the coating.

This study was focused to the assurance of higher durability of hard coatings by applying of keyhole mode LC method. The aim of this research was to check the hypothesis by comparing two types of differently produced coatings: the first one had a low dilution of the clad layer and the second one in contrast had higher rate of dilution due to cladding with deep (keyhole) penetration in to substrate. The hypothesis of this research was that applying of the first layer of coatings onto steel substrate with keyhole penetration mode allows achieving smooth gradient of properties in the coating-substrate system using dissimilar steels. As a result it may provide a gradual redistribution of trough-depth residual stresses as well as better resistance to external stress during cyclic load in metal forming and stamping processes.

2. Materials, equipment and experimental details

High-speed steels (HSS) present high strength, hardness and wear resistance by application of corresponding heat treatment. Besides the applicability for cutting tools, these steels are also used for producing of stamping tools. Herewith HSS are operated under especially severe conditions, at pressures in above of 2,000 MPa and heating to temperatures of 300–500°C for mass and large-scale production, when it is necessary to ensure high durability of the die tooling [8]. By this reason the filler material selected for this research was HSS globe-shape powder AISI M2 (EN HS6-5-2) with particle size of 53–150 μm. As a substrate cold work tool steel plate AISI D2 (EN X153CrMoV12) was used with dimensions of 100×50×10 mm with hardness according to the material certificate ca. 255 HB. The work surface of the plate has been mechanically grinded before treatment. Chemical compositions of the materials are listed in the next table 1.

| Table 1. Chemical composition of powder AISI M2 (1), substrate AISI D2 (2) |
|-----------------|-------|-------|-------|-------|-------|-------|-------|
|                | C     | Mn    | Si    | Mo    | Cr    | V     | W     |
| 1.              | 0.85–1.05 | 0.20–0.40 | 0.20–0.40 | 4.50–5.50 | 3.75–4.50 | 1.60–2.20 | 5.50–6.80 |
| 2.              | 1.45–1.60 | 0.20–0.60 | 0.10–0.60 | 0.70–1.00 | 11.00–13.00 | 0.70–1.00 | –     |
Experimental work of laser cladding was carried out using precise industrial robot system (KUKA), which consists of 6-axis manipulator KR 30 HA and 2-axis positioner DKP-400. The manipulator is equipped with coaxial powder supplying cladding head WT03 (Permanova Lasersystem) and Yb-fiber laser YLR-1000 (IPG Laser) with 100 μm optical fiber and 1000 W power supply. Optical system provides laser beam spot size in a focus plane of about 570 μm with a Gaussian intensity distribution. Powder mass feeding performed with the powder feeder TWIN-10-C (Sulzer Metco), where the argon was used as a carrier gas and as a shielding gas to prevent oxidation of the powder and the melt pool. Robotic laser workcell equipped for LC process is presented in the next figure 1.

![Figure 1. Laser cladding equipment of robotic workcell](image)

![Figure 2. Laser cladded HSS coatings created by: a) regime no. 1, b) regime no. 2](image)

Coatings during laser cladding are created by partly overlapping of sequential single cladding tracks and due to a large amount of process parameters different effect on coating properties and quality can be obtained. By this reason, in order to find out the necessary regimes for producing of single clad bead with required parameters of form preliminary experiments have been executed. Further, to achieve the aim of this research two coatings with different structures in interface were created by using various regimes, which varied in distance of laser beam defocus (F, mm) and spacing between adjacent clad beads, i.e. overlap ratio (OR). The separate parameters of these regimes, which correspond to produced coatings are shown in the next table 2, where the 1st coating (figure 2, a) was created by regime no. 1 and the 2nd coating (figure 2, b) by regime no. 2 respectively. The rest process parameters stayed unchanged: laser power 630 W; scanning speed 700 mm·min⁻¹; carrier gas flow (Ar) 5 l·min⁻¹; shielding gas flow (Ar) 16 l·min⁻¹; powder mass feed rate 7 g·min⁻¹. The cladding head all along process was located perpendicularly to the surface being treated, directing laser beam toward the work surface in the specified focus distance.

| Parameter’s description - ID       | Regime no. 1 | Regime no. 2 |
|-----------------------------------|--------------|--------------|
| Laser beam defocus – F, (mm)      | +5           | 0            |
| Overlap ratio – OR, (mm)          | 0.6          | 1.3          |
Then plates with experimental coatings were transversely cross-sectioned, polished and etched with Nital (4%). The quality of cladded coatings has been evaluated by examination of morphology of transverse cross-sections using scanning electron microscope – SEM (TESCAN-VEGA-LMU II), elemental composition in coatings was determined using energy dispersive spectrometry – EDS analysis (EDS module INCAx–act Oxford Instruments).

Mechanical properties were investigated by analysis of microhardness distributions on coatings cross-sections and tribological behaviour of coatings finished surfaces. For determination of microhardness distributions in the coating-substrate system, material layers were sequentially removed from specimen’s cross-section 5 times by a depth of 0.5 mm using grinding and polishing equipment LaboPol-30/LaboForce-100 (Struers). After removing of each material layer stepwise microhardness measuring have been done in automatic regime by pre-set pattern of rectangular array using the hardness tester Falcon 503 (INNOVATEST). Measurements were performed by Vickers method according to ISO 6507-1 standard with 200 g load and 10 s hold time on the each indentation point. As a result, 3D microhardness distribution maps in the coating-substrate system were obtained.

During tribological research dry friction tests have been executed on the super mirror finished surfaces of coatings (Ra ≈ 0.005 µm) using “ball-on-disc” tribometer (CSM Instruments) and in accordance with ASTM G99-95A standard. On the run of test specimen was used as a disc, but a high-strength steel ball (surface hardness ca. 62 HRC) was used as a counter-body. Experimental settings for the friction tests were the following: diameter of the ball: 6 mm; material of the ball: 100Cr6 (DIN EN ISO 683-17); ball’s contact radius: 3 mm; normal load: 3 N; sliding speed: 0.05 m/s; room temperature: 25±1 °C, relative humidity 41±5%. Tests were performed by 3 mm radius of rotation on each coating with sliding distance of 500 laps. Following the tribo tests 2D profiles of each wear tracks were obtained by means of profilometry using surface roughness tester Surtronic 25 (Taylor Hobson). Wear rate of the ball was determined by measuring of wear area using digital microscope KH-7700 (Hirox).

3. Results and Discussion
In the course of the comparative analysis both created coatings were investigated on the basis of morphology, elemental composition of clad layer, microhardness distribution along the depth of coating cross-sections and tribological properties of coatings finished surfaces.

3.1. Morphology
During examination of coatings transversal cross-sections by SEM it was noticed that produced coatings had good metallurgical bonding with the substrate, no exfoliations were found. Figures 2 and 3 present these cross-sectional views with reference measurements and conditionally separated zones of coating-substrate system. These zones are marked in following way: clad layer or clad zone (CZ), interface zone (IZ) and base material (BM). Also concerning the 2nd coating keyhole penetration zone (KPZ) can be seen, which consist of alternating deep molten pools and appears as an extension of IZ. The thickness of CZ was measured excluding the surface waviness i.e. effective thickness of the coating. For the 1st coating this dimension was at the average rate of 650 µm and for the 2nd coating of 380 µm respectively. The depth of penetration (D) was significantly larger in case of the 2nd coating, because of deep melting peculiar to the keyhole mode. This is due to scanning of the processed surface in the focal plane of laser beam and along with the characteristics of used optical system results in high laser power density at about 4.9·10^7 W·cm^{-2}. Hereby whole depth of penetration for the 2nd coating was defined as D = D_{L} + D_{z} and in average amounted to 1625 µm. However the 1st coating showed significantly smaller depth of penetration with its measured size at about 200 µm. Therewith it was noticed, that coating with keyhole geometry contains gas voids which in a greater degree were located near the root of keyhole. This type of imperfection is also typical for laser welding and may be referred to the gas bubbles formation in the keyhole shaped melt pool due to material evaporation [9].
The examination at a higher magnification showed that microstructure of both coatings had mixture of cellular and dendritic solidification grain structures. In the CZ (figures 5 and 6) mixture of grains was equiaxed, which corresponds to the homogeneous temperature field in all the directions. In areas near the substrate, especially in case of the 2nd coating, microstructure had larger proportion of columnar dendrites, growing in direction from the fusion line to the middle of the clad bead. Generally, comparing these two coatings, the finest scale of graininess corresponds to the 1st. First of all it can be associated with lower heat input due to the action of the defocused laser beam which causes a higher rate of solidification. As it was reported earlier [10] microstructure of M2 coatings typically consists of martensite, retained austenite and carbide eutectic at grain boundaries as well as formations of secondary carbides through the reheating by adjacently deposited cladding layer. However in present work during observation with SEM these microstructural constituents under used etchant were indistinguishable.
3.2. Elemental composition
In order to determine average chemical composition of the coatings influenced by differently diluted substrate 3 EDS probes have been taken in coatings CZ (figures 7 and 8). The results of this analysis are presented in the next table 3.

As it is seen in the 1st coating content of alloying elements (Cr, Mo, W, V) is virtually the same as in the original powder composition. However in the 2nd coating content of Mo, W, V in CZ was significantly decreased and saturates larger amount of Cr and Fe, which is related to the largest depth of fusion of the substrate and as a result higher level of interdiffusion was achieved. Therefore, analysis showed that degree of mixing between the clad material and the base material was greater for the 2nd coating.

![Figure 7. Regions for EDS analysis – 1st coating](image1)

![Figure 8. Regions for EDS analysis – 2nd coating](image2)

|      | Spectrum 1 | Spectrum 2 | Spectrum 3 | Mean | Std. deviation | Max. | Min. |
|------|------------|------------|------------|------|----------------|------|------|
| C    | 1.52       | 3.04       | 1.07       | 1.88 | 1.03           | 1.96 | 1.49 |
| V    | 2.02       | 2.11       | 2.05       | 2.06 | 0.05           | 2.11 | 1.26 |
| Cr   | 4.85       | 4.72       | 4.66       | 4.74 | 0.09           | 4.85 | 8.61 |
| Fe   | 80.66      | 79.64      | 80.91      | 80.40| 0.67           | 80.91| 82.73|
| Mo   | 5.26       | 5.25       | 5.27       | 5.26 | 0.01           | 5.25 | 2.88 |
| W    | 5.70       | 5.24       | 6.03       | 5.66 | 0.40           | 5.24 | 2.26 |
| Total| 100.00     | 100.00     | 100.00     |      |                |      |      |

**Table 3. Results of EDS analysis**

Elemental composition in CZ of the 1st coating (wt.%)
3.3. Microhardness

In order to investigate distribution of properties in coating-substrate system microhardness measurements have been fulfilled by rectangular pattern on 5 sequential cross-sections of coatings. For the 1\textsuperscript{st} coating (figure 9) 75 points of measurements were done on each stage of material removal (5 rows by 15 points forms rectangular array with hatch spacing of 350×350 µm). While for the 2\textsuperscript{nd} coating (figure 10) 77 points of measurements have been performed (7 rows of 11 points forms rectangular array with hatch spacing of 650×350 µm).

![Figure 9. Hardness test pattern for the 1\textsuperscript{st} coating](image1)

![Figure 10. Hardness test pattern for the 2\textsuperscript{nd} coating](image2)

Analysis revealed that the difference in LC methods has significant influence on the microhardness of coating. The 1\textsuperscript{st} coating, which has had lower dilution from the substrate, appeared almost two times highest values of microhardness in comparison to the coating with larger amount of dilution. The average microhardness value of CZ for the 1\textsuperscript{st} coating was 895 HV0.2 and 490 HV0.2 for the 2\textsuperscript{nd} coating respectively. The higher hardness can be attributed to the finest microstructure of the coating.

The following figures 11 (a, b) and 12 (a, b) show 3D graphs of microhardness distribution in cross-sections for both coatings according to the mean value of 5 layers measurements. As it is seen the 1\textsuperscript{st} coating demonstrates a fairly uniform order of microhardness along the overlapping direction of cladding beads (X axis). However abrupt transition of values along the depth (Y axis) is evident. In its turn, the 2\textsuperscript{nd} coating displays heterogeneity of properties along X axis with appreciable peaks of increased microhardness, which apparently corresponds to the cavity between contiguous keyholes in KPZ. Obviously, to exclude these unfavorable peaks, the smallest step of overlap should be used.

![Figure 11. Vickers 3D surface plot of the microhardness distribution (a) and microhardness mapping (b) on the transverse cross-section of the 1\textsuperscript{st} coating acc. to the mean value of 5 layers measurements](image3)
Figure 12. Vickers 3D surface plot of the microhardness distribution (a) and microhardness mapping (b) on the transverse cross-section of the 2nd coating acc. to the mean value of 5 layers measurements

By comparing both trough-depth distribution profiles of microhardness between produced coatings the smooth transition for the 2nd coating was obtained (figure 13). Considering that hardness correlates to the strength of the material, therefore the similar gradient can be inherent in the distribution of internal stresses in the coating-substrate system.

Figure 13. Vickers microhardness profiles on transverse cross-sections of coatings as function of depth

3.4. Tribological performance
As it is well known high hardness of the coating is often not the dominant factor for ensuring the best functional properties. Therefore tribological analysis of produced coatings was fulfilled to define coefficients of friction (CoF) and their changes during the testing. In this course three tests have been performed under the same conditions for each coating. Figures 14 and 15 demonstrate some friction curves for both coatings showing the variation of CoF in relation to sliding distance. At the start of the test CoF increased rapidly close to the value of 0.6 then followed by decrease with different slope angle to the value of about 0.45. The drop of CoF may be associated with formations of wear debris which prevent direct [11] contact between two surfaces of tribological couple. After running-in period CoF tends to gradual increase again close to the value of 0.6 followed by same degree of decrease until the test stopped. Generally the 2nd coating presented sharper peak in running-in period compared with the 1st coating, but then friction curves of both coatings had very similar trends.
Overall average CoF values of three tests for both coatings were very close, namely for the 1st coating amounted to 0.511 and for the 2nd coating it was 0.503. Maximum value of CoF during tests for the 1st coating reached 0.675 and for the 2nd coating up to 0.631 respectively.

**Figure 14.** Friction curve for the 1st coating  
**Figure 15.** Friction curve for the 2nd coating

Examination of worn tracks by means of profilometry revealed that wear of the coating actually was absent. Evenly for the both coatings some portion of the material from counter-body was adhered on the tested surface i.e. positive depth of wear track was ascertained (figure 16). Maximum adhered layer height varied from 0.36 to 1 µm. Such a wear pattern indicated that the material of coatings was more resistant against wear than the test ball. Wear areas of the ball for the 1st coating ranged from 0.096 to 0.129 mm² and respectively for the 2nd coating from 0.099 to 0.105 mm². Consequently analysis showed that despite the difference in hardness both coatings had essentially equivalent tribological properties.

**Figure 16.** The profilogram of worn track (coating no. 2)

### 4. Conclusions

In this paper the keyhole mode laser cladding for creating of functionally graded coatings was presented. Thereby in order to check the hypothesis of the study two types of high speed steel coatings have been compared. As a result, the main points can be noted as follows:

- Although coating with keyhole mode in penetration had lower hardness of clad layer due to a larger amount of dilution the smooth transition of properties in the interface has been obtained.
- Despite the significant difference in hardness both coatings demonstrated very similar tribological properties.
• Through the peculiarities of keyhole mode laser cladding the composite structure of the coating can be achieved, where properties of interlayer, which is intended to bond dissimilar steels, provides keyhole penetration zone. This in turn can decrease the gradient of trough-depth residual stresses generated when materials with different coefficient of thermal expansion are used. Accordingly by having control over structure of keyhole penetration zone it is possible to manage the gradient of properties in coating-substrate system. Therefore applying of this method may exclude deposition of the buffer layer for cladding of hardfacing coatings. Also it can contribute to the improvement fatigue strength of stamp tooling, as well as durability increase of thermal barrier coatings.

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