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Functionally graded multi-layers by laser cladding for increased wear and corrosion protection

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Abstract

The growing competition in the die casting industry requires extension of the lifetime of the moulds. This major demand can be fulfilled by increasing the wear resistance of the mould with hard surface layers to reduce erosion. Combining this feature with high tensile strength and high ductility, thermal or stress induced cracking during the casting process with its cyclic thermal and mechanical stresses can also be minimised or inhibited. However, commonly used hot working tool steels are limited regarding the required properties. Laser cladding is an established technique to increase wear and corrosion protection locally and it offers the possibility to combine properties by multi-graded layers.

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1. Introduction

Due to the demand of the aluminum die casting industry to increase the lifetime of moulds, existing hot working tool steels are constantly being improved. However, it is questionable if a homogeneous material can meet the various requirements for the complex die casting process which are sometimes contradictory like ductility and wear resistance in different sections of a die cast mould.

In most die casting processes cracks and wear caused by thermal stresses and erosion are the main factors that limit the lifetime of moulds. Cyclic thermomechanical stresses near the surface of the mould cavity caused by contact with the liquid aluminum melt with a temperature of approx. 650°C and subsequent cooling to a temperature of 200°C lead to thermal cracks. In areas of the mould, where the material failure is caused by thermal stresses a high ductility and high thermal shock resistance is required. In mould sections where the liquid metal is pressed around sharp corners, the die is stressed by erosion.

To increase the lifetime of these sections, the required properties are a high hardness near the surface and a high corrosion resistance.

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These properties can be achieved by applying materials tailored to the specific failure mechanism of the mould sections. A single-layer coating can fulfill the requirements for hardness, corrosion resistance and thermal shock resistance of the surface. However, the transition zone to the base material might cause fatigue failure due to different thermal and mechanical properties which induce thermal and mechanical stresses. This disadvantage can be at least minimized by applying graded layers with a smooth transition between base material and coating.

The use of graded materials that combine the characteristics of different materials gives rise to new property profiles that can be customized to specific wear pattern [1-5]. The laser cladding process offers the possibility to build up graded layers by applying layer by layer with variation in composition.

2. Laser cladding process

Laser cladding is a powder-based process to build up 3D parts layer by layer [5]. The powder can be fed either off-axially or coaxially. Figure 1 shows a discontinuous coaxial powder feed nozzle used for the experiments. Three individual powder gas streams are fed into a powder gas stream focus on the surface of the substrate. The main advantages of the laser cladding process are high precision, a minimized heat affected zone (HAZ), low distortion and the variety of materials. Nearly every metallic material can be clad. Low melting alloys based on aluminium can be used as well as nickel-based alloys, intermetallics (e.g. titanium aluminide) and high-melting point metals such as tungsten.

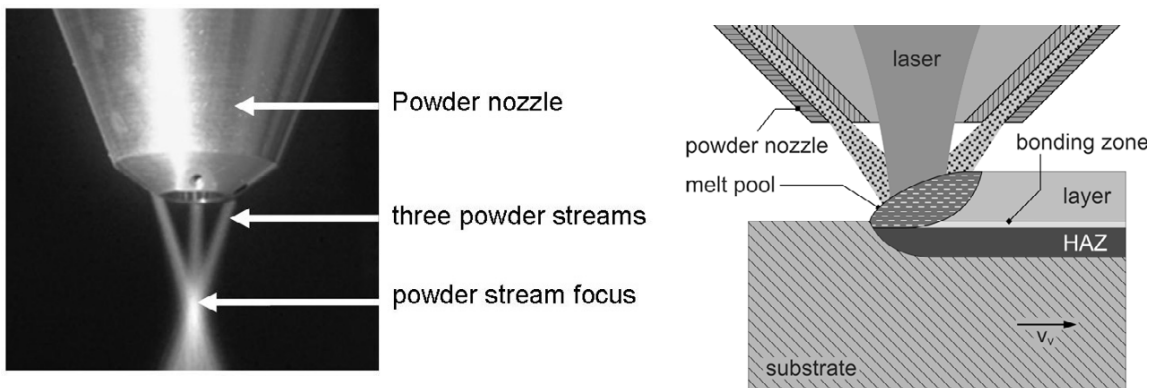


Fig. 1. (a) Discontinuous coaxial-powder feeding; (b) Principle of laser cladding process

The powder is fed to the interaction zone in a carrier gas stream (helium or argon). The laser beam melts the powder material particles and a thin layer of the base material (Figure 1b). After solidification a layer with a metallurgical bonding to the substrate is produced. By adaptation of the process parameters such as velocity, powder feed rate and laser power, the thickness of the built layer can be varied typically from 0.1 up to 3 mm in a single pass. With multi-layer cladding thicker layers can be produced. This method is also used for the production of graded layers.

3. Equipment and materials

Experiments are carried out using a 5-axis handling system equipped with a 1kW fiber-coupled diode laser. Cladding was carried out with a focus diameter of 1.1 mm and an overlap of single tracks of 0.5 mm. The powder is fed with a twin powder feeder (Sulzer Metco Twin 10 C) utilizing a volumetric method of feedrate control by a grooved rotating disc to deliver a precise quantity of powder. The rotation speed of the disc is CNC-controlled to adjust the feed rate automatically during the process. For variation of the powder feed rates in a huge range discs with a 3.5 mm width and 0.5 mm deep groove are used. The powder feed nozzle is a discontinuous coaxial nozzle as shown in Figure 1. Helium is used as carrier gas for the feeding of the powder into the interaction zone. For each powder hopper the gas volume flow is adjusted to 3.5 l/min to guarantee a continuous mass flow without any fluctuations. The focus diameter of the powder gas stream is approx. 1.5 mm. The particle size range of the powders

is 45-100 μm . The used additive materials are iron-, cobalt- and nickel-based alloys (Tab. 1). Tempered 1.2343 is used as substrate material for the future build up of graded layers on die casting moulds. Marlok is a high strength maraging steel with a high thermal fatigue resistance. For the graded layers Marlok is used as the bottom component due to the advantage of a high ductility which can stop cracks from growing into the substrate. 1.2365 and Dievar, two typical hot working steels, are similar in the alloy composition. Due to their good high temperature strength they are used as the near-surface component in graded layers in combination with Marlok. Stellite 31 is a cobalt-based alloy with a wear and corrosion resistance suitable for high temperature applications. The microstructure of Stellite 31 is not sensible to tempering which makes it superior to most steels which lose hardness and strength during die casting. Stellite 31 is used as top component in combination with Marlok.

Table 1: Composition of the used powder and base materials in wt.-% and grain size of the particles

material	range of grain size	Contents of alloys [wt.-%]										
		C	Co	Cr	Fe	Mo	Mn	Ni	Si	Ti	V	W
1.2343	/	0,35	/	5,15	Base	1,15	0,30	/	1,00	/	/	/
1.2365	45-100 μm	0,31	/	3,00	Base	2,80	0,30	/	0,25	/	0,55	/
Dievar	45-100 μm	0,35	/	5,00	Base	2,30	0,50	/	0,20	/	0,60	/
Marlok	45-100 μm	0,008	10,50	0,30	Base	4,50	0,05	14,00	< 0,10	0,20	/	/
Stellite 31	45-125 μm	0,50	Base	25,50	/	/	/	10,50	/	/	/	7,50

4. Processing

For building up graded layers two different powders are fed simultaneously into the interaction zone, where both are melted by the laser radiation. The alloy composition of the solidified layer is a mixture of both materials. By changing the powder feed rates step-by-step a smooth transition from one component to the other can be achieved. The first step is to find a set of parameters for each material which is suitable for building up layers without cracks and porosity with a preset layer thickness of 300 μm (this is chosen to attain an aspect ratio of width (approx. 1 mm) to height in the range of 3-4 to avoid failures in the bonding zone). This procedure is necessary to achieve constant layer thicknesses during the build up process of the graded material. The attempt to keep the total absolute powder feed volume constant is not suitable regarding the demand for a constant layer thickness. For a given set of parameters the disc speed of the feeder varies for the different materials, because of the differences in absorptivity, grain size, powder density and flowability. The powder feed rate (= disc speed) of each material to build up a layer with the preset thickness is set as 100 %. The powder feed rate in the following diagrams is given as percentage of the powder feed rate required for each material to achieve the layer thickness of 300 μm .

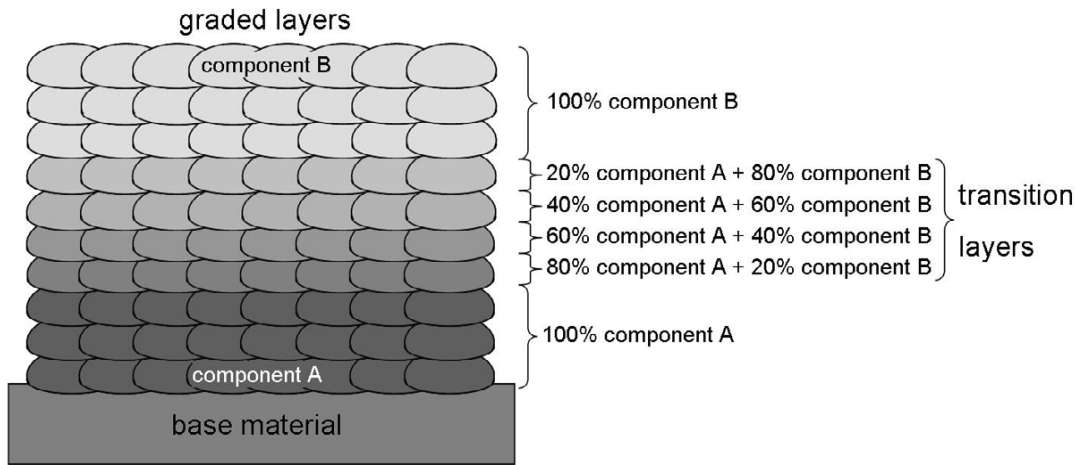


Fig. 2. Schematic drawing of the build up of graded layers

The next step is to build up multi-layer samples with a constant ratio of both materials by using the determined powder feed rates to investigate whether certain composition lead to undesired effects like embrittlement, pores and cracks. The powder feed rates of both materials are varied in steps of 20% or 25% and added up to 100%.

Finally, graded layers are built up (Fig. 2) by a gradual variation of the powder feed rates, which is based on the previously determined values to achieve a constant layer thickness. The first (the last) three or four layers of the gradient are made of 100 % of component A (B) to decrease the influence of the mixing component A with the melted base material and to obtain the pure alloy of component B near the surface (which is in contact with the aluminum melt). The contents of the main alloying elements are analyzed by energy dispersive spectrometry (EDS) to investigate the compositional gradient from one component to the other.

During all steps of experiments the microstructure is investigated by optical microscopy and hardness profiles are measured with a micro Vickers hardness tester.

5. Results

5.1. Combination Marlok + Stellite 31

Sets of parameters to build up graded layers without porosity and cracks are determined for selected combinations of materials. A defect free build up of samples made of a combination of iron-based Marlok and cobalt-based Stellite 31 material is achieved by increasing the laser power at higher contents of Stellite 31 (Table 2).

Table 2. Process parameters for fixed mixtures of Marlok and Stellite 31

Sample- No.	Component A Marlok	Powder disc speed Component A [min ⁻¹]	Component B Stellite 31	Powder disc speed Component B [min ⁻¹]	Laser power [W]	Velocity [mm/min]
1	100%	1,70	0%	0	300	400
2	75%	1,275	25%	0,25	325	400
3	50%	0,85	50%	0,50	350	400
4	25%	0,425	75%	0,75	375	400
5	0%	0	100%	1,00	400	400

Figure 2 shows the microstructure of various compositions. An increasing dendritic microstructure with increasing fraction of Stellite 31 is observed. No cracks are detected and only a few small pores can be found. The

hardness of the samples made of a composition of Marlok and Stellite 31 is significantly lower than that of the pure alloys (Figure 3).

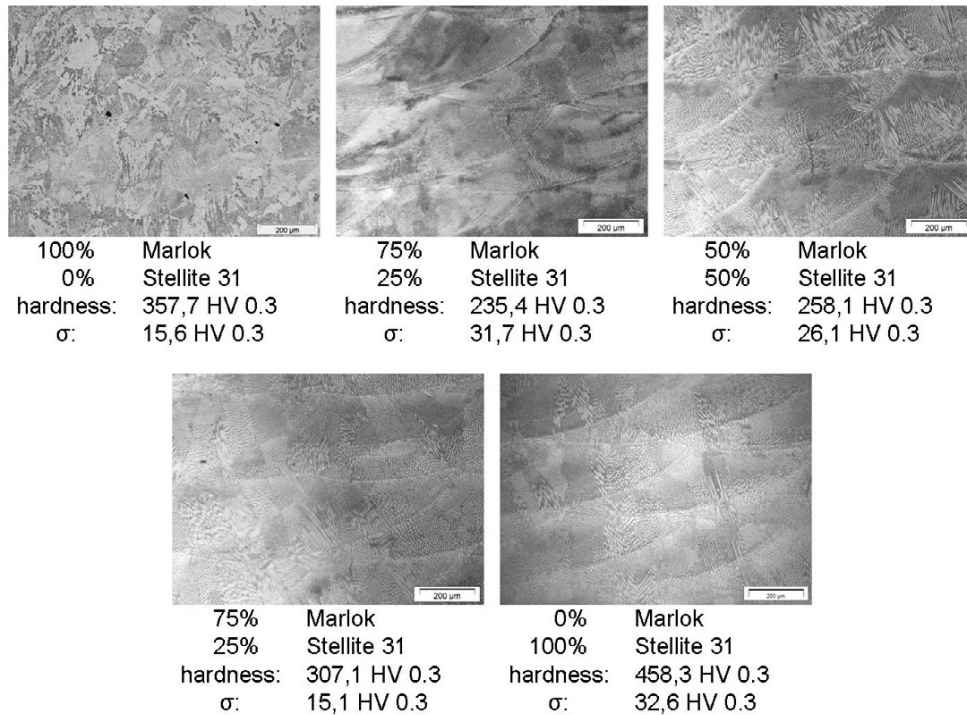


Fig. 3. Microstructure of layers made of Marlok and Stellite 31 with a constant mixture ratio

With the parameters in table 2 defect-free graded layers with Marlok and Stellite 31 are built up. The EDS-Analysis of the main alloy elements (Fe, Cr, Co) show that the composition change through the graded layer is nearly linear which proofs that a smooth transition from one alloy to the other is achieved. In the graded area a significant drop in hardness is detected (in accordance to fig. 3). The reason for this is not yet understood. The low hardness of 220HV of the substrate is caused by the use of annealed base material 1.2343.

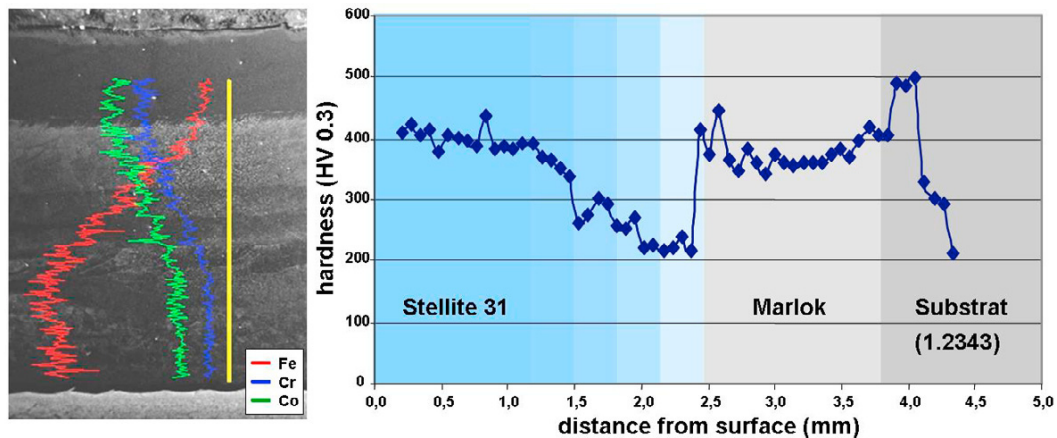


Fig. 4. EDS-Analysis of a graded layer of Marlok and Stellite 31 (left); hardness profile within this layer (right)

5.2. Combination Marlok and 1.2365

Several samples made of a combination of Marlok and 1.2365 are built up without defects with a constant laser power of 300 W and a velocity of 400 mm/min. The powder feed rate is changed in steps of 20 %. The microstructure of the samples with contents of both materials shows a fine martensitic structure and an increasing hardness with an increasing content of 1.2365 (Fig. 5). No cracks and only a few small pores are found.

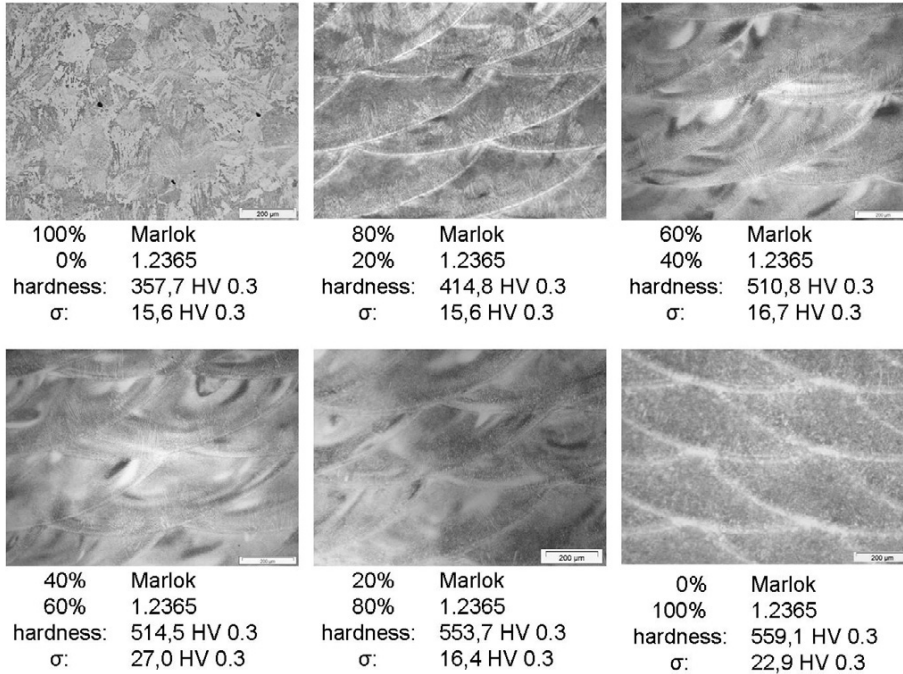


Fig. 5. Microstructure of layers made of Marlok and 1.2365 with a constant mixture ratio

The gradient of the hardness in the graded layers made of Marlok and 1.2365 is nearly linear (Figure 6). The fluctuation of hardness in the section of 100 % 1.2365 material is caused by a tempering of the martensite in the HAZ of the previous layer. A post weld heat treatment is planned to eliminate this effect. The hardness gradient in graded layer is intended to increase ductility and in consequence to avoid or stop cracks caused by thermal and mechanical stresses. The EDS-Analysis of the graded structure proofs the linear change of the main alloying elements in the transition zone.

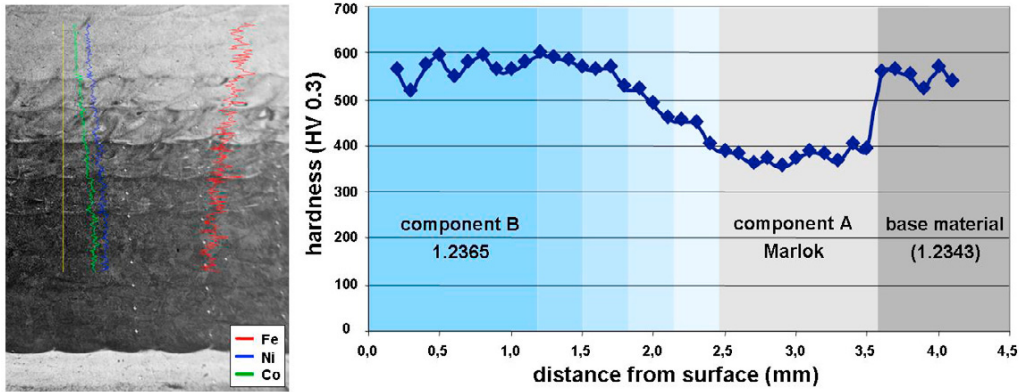


Fig. 6. EDS-Analysis of a graded layer of Marlok and 1.2365 (left); hardness profile within this layer (right)

5.3. Combination Marlok + Dievar

Samples of the iron-based materials Marlok and Dievar are build up defect free with a constant laser power of 325 W and a velocity of 400 mm/min. To test the mechanical properties of cladmed material tensile tests are done and compared with data of wrought material and heat treated die casting tool steel 1.2343 with a hardness of 46 HRC (Fig 7). These tests were carried out at the Institute for joining and welding technology (ifs) at the TU Braunschweig. The laser cladmed samples are heat treated for 2 hours at a temperature of 580°C prior to tensile testing to reduce residual stresses. This heat treatment is recommended for Marlok material to increase the hardness up to 500HV. The results show that the cladmed Marlok sample has a significant larger breaking elongation than wrought Marlok material (Tab. 3) and only a slightly lower tensile strength. In comparison to the reference material 1.2343 it has nearly the same tensile strength like the reference material 1.2343 (Fig. 7). The cladmed Dievar sample has a lower tensile strength, nearly the same fracture elongation but an increased hardness of approx. 700 HV (\approx 60 HRC) in comparison to wrought Dievar material (Tab. 3) with a hardness of 545 HV (52 HRC). Both cladmed materials show superior properties in comparison to wrought 1.2343.

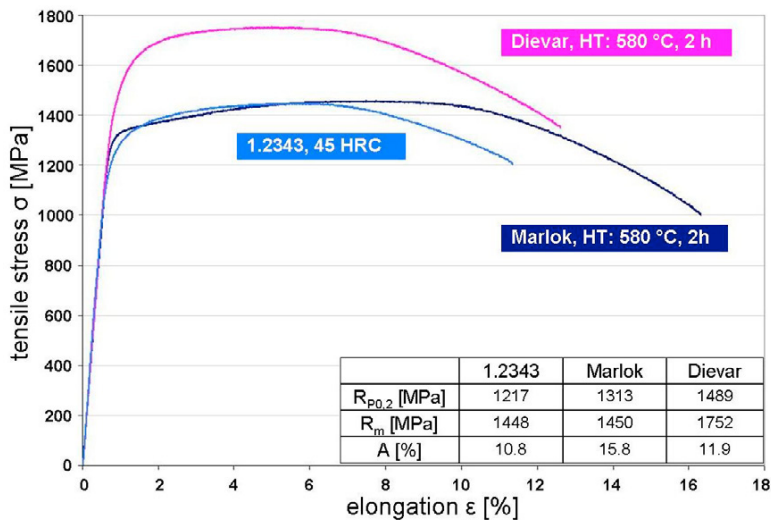


Fig. 7. Stress-Elongation-Diagram for laser cladmed Marlok and Dievar and wrought and conventionally heat treated 1.2343

Table 3. Mechanical properties of wrought Marlok and Dievar [6], [7]

material	R _e [MPa]	R _m [MPa]	A [%]
Marlok (47-51 HRC)	1500	1600	8-12
Dievar (44HRC)	1210	1480	13
Dievar (48HRC)	1380	1640	13
Dievar (52HRC)	1560	1900	12,5

Graded layers with Marlok at the bottom and Dievar at the top are built up without cracks and low porosity. The surface layers made of Dievar have a hardness between 650 and 700 HV which is an increase of nearly 30 % in comparison to the 1.2343 material with a hardness of 460 HV. A linear increase of hardness is achieved by a smooth change of materials with four transition layers. The fluctuation of hardness in the top layers made of Dievar can be eliminated by a post weld heat treatment.

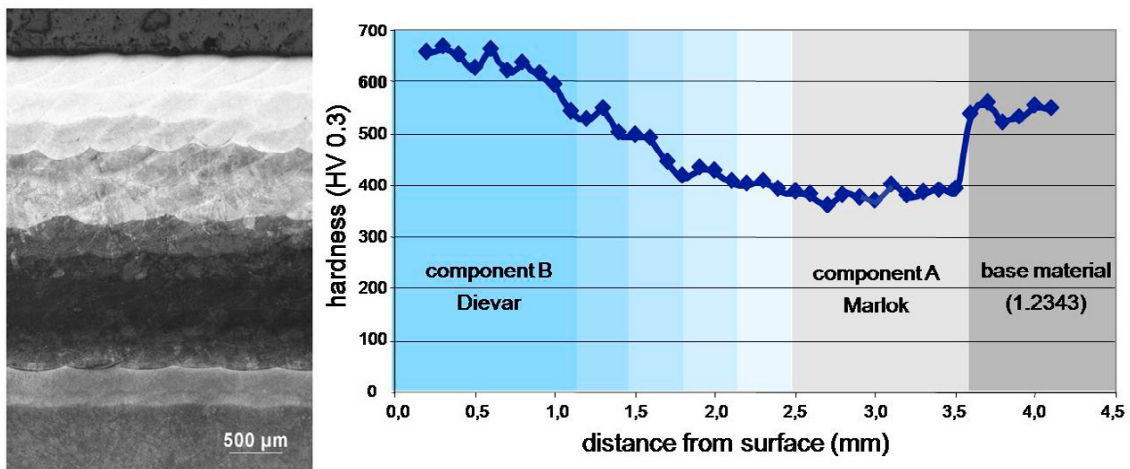


Fig. 8. Cross section of a graded layer of Marlok and Dievar (left); hardness profile within this layer (right)

6. Conclusions

Experimental investigations show that laser cladding can be used to build up graded layers with a smooth transition of composition. The cladded layers are assembled without any cracks and only low porosity. Combinations of iron-based materials have a nearly linear increase of hardness in the transition layers of the gradient. The cladded Marlok and Dievar materials have superior properties in comparison to wrought 1.2343 hot working steel. With appropriate material combinations on iron- and cobalt-base graded layers free from porosity and cracks can be produced.

Future activities will be concerned with the determination of properties like thermal shock resistance of graded layers. Subsequently, a mock-up mould will be manufactured using selected graduated materials and tested in a die-cast moulding machine to access the quality of the gradient under operating conditions. Finally graded layers will be applied on real die casting tools for field tests.

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