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Electron Beam Liquid Phase Surface Technologies for Components Made from High-Loaded Aluminium Materials

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An extremely promising option to protect the high-loaded function surface of engine components in motor vehicles against wear is provided by electron beam (EB) liquid phase surface treatments with additives (EB alloying). But in connection with spray-formed aluminium alloys, this is a great challenge because of the special production process, the exotic chemical composition and the microstructure of these materials. Thanks to special beam deflection techniques, EB energy distribution functions are programmable in a very flexible way if the characteristics of both material (base and deposition material) and component (geometry, contour) are taken into consideration, and therefore, they are exactly adaptable to different requirements. By means of exemplary investigation of valves, the effect of EB technologies and parameters, type and composition of additives (Co based materials) and the deposition method on the quality and properties of the layer will be demonstrated. The alloyed layers are characterised with regard to their macroscopic properties (geometrical characteristics, macroscopic defects et al.), microstructure (type and morphology of intermetallic compounds et al.), thermal resistance (annealing test up to 300°C) and properties (hardness, wear resistance).

Keywords: *electron beam alloying, spray-formed aluminium, valve, Co additive*

1. Introduction

Engine components in motor vehicles are subjected to permanently increasing mechanical, tribological and corrosive stresses [1]. The successful implementation of lightweight constructions, especially fast-moving or rotating components, e.g. valves, pistons, requires the use of materials with low density and sufficient thermal stability [2]. Therefore, the use of spray-formed aluminium alloys is taken into consideration again [3, 4].

A promising option to protect the functional surface against wear is provided by EB liquid phase surface treatments with/without the use of additions. These technologies allow locally specific changes of microstructure and characteristics in a basic material layer [5]. As a result of fast heating and cooling, phases and microstructures in the surface layer are formed by thermodynamic balance, among other things [6, 7].

But in connection with spray-formed aluminium alloys, this is a great challenge. The special production process of Al alloys by spray forming allows the production of “exotic” chemical compositions and microstructures of these materials [8]. Cu, Ni and Co additives were tested with regard to tribological loading conditions. In formerly published investigations EB alloying was shown to provide a good ability regarding sufficient hardness and improved wear resistance [9, 10]. However, these alloyed layers are limited when it comes to thermal resistance, this especially applies to Cu based alloyed layers.

New investigations deal with Co additives because of the possibility to generate thermally stable compounds. Co base materials are well known as stellites (Co-Cr-W-C) used for high wear resistant hard facing. While Co supports toughness, additional elements, such as Ni, Fe, form compounds or carbides (W, Cr) and W, Mo act as solid solution hardeners [11-13].

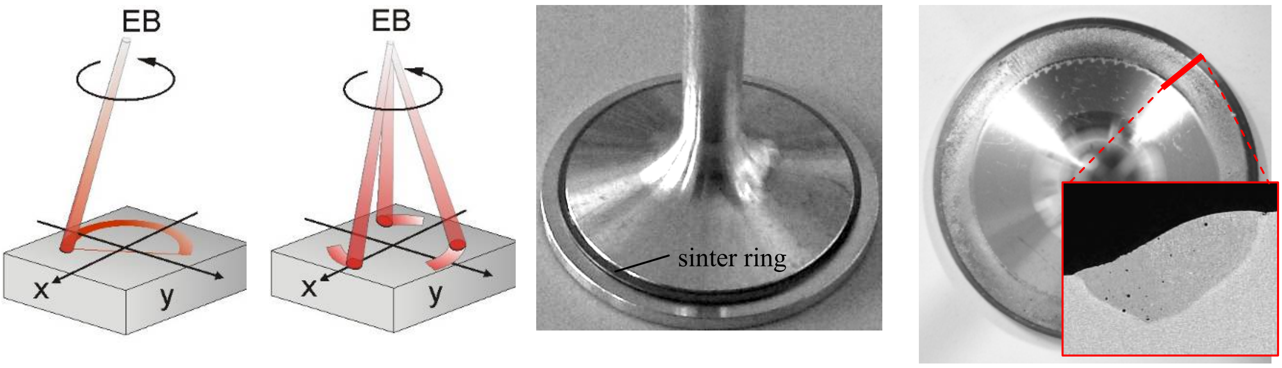
2. Beam deflection technique

The EB is an especially suitable tool for performing liquid phase surface treatments of components made of aluminium materials because of [5]:

- surface independent energy input → excellent energy transfer
- high beam and overall efficiency (~90% / 65%) → high process efficiency
- high heating and cooling rates (≤ 10^4 K/s) → short periods of treatment, special structure and properties relations
- vacuum process → no oxidation, good outgassing
- excellent beam guidance possibilities → multi-spot deflection technique

Thanks to special beam deflection techniques, EB energy distribution functions are very flexibly programmable if the characteristics of both material (base and deposition material) and component (geometry, contour) are taken into consideration, and therefore they are exactly adaptable to different requirements.

With regard to the presented application, different beam deflection techniques are applied. One spot technique (Figure 1a) is relatively simple and allows to generate base parameter sets. The developed multi-pool spiral technique (Figure 1b) is a very complex process with some benefits, like high productivity, fixed sinter ring (no distortion), pre-heating effect (leading pool) etc.



a) single spot b) multi spot c) additive deposition d) EB alloyed valve

Fig. 1 electron beam deflection techniques and valve before and after EB alloying

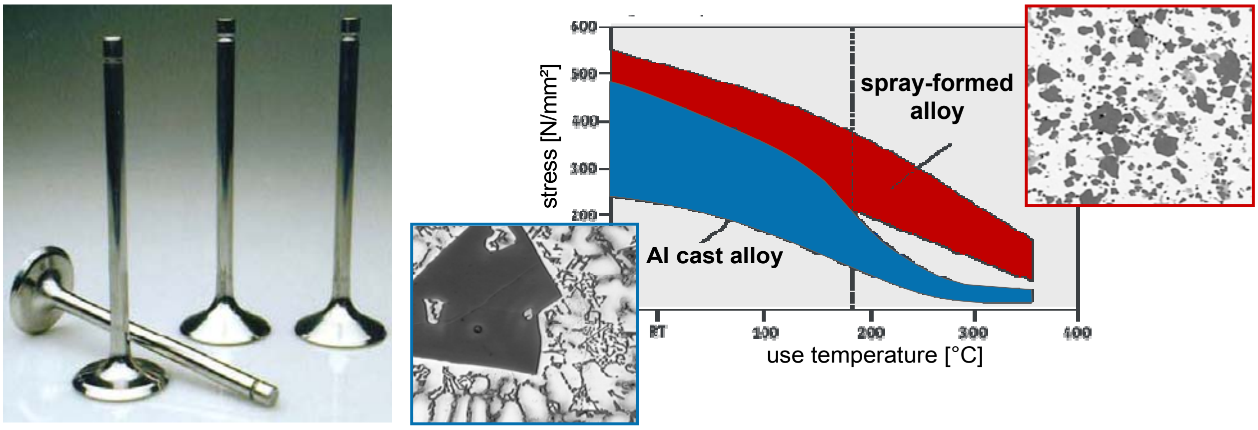
3. Base and deposition materials

Base materials used for these investigations are two spray-formed aluminium alloys differing in content of silicon iron, nickel and copper (Table 1). The special production process allows to design a load-related chemical composition in a wide range, e.g. high content of Fe or Ni for improved heat resistance respectively higher use temperature (Figure 2b).

Table 1 Chemical composition of base materials

	element concentration [wt.%]					
	Al	***Si***	***Mg***	***Fe***	***Ni***	***Cu***
alloy 1	base	17	-	6,6	2,1	-
alloy 2	base	21	0,4	0,3	7,7	2,5

The microstructure of used base materials consists of an Al matrix with very fine (<5 µm) and exclusive primary Si particles (Si_P), additional very fine dispersoids as well as different intermetallic phases depending on the type and amount of alloying elements (Figure 3a) caused by the typical high cooling rates and the associated microstructure formation under conditions of disequilibrium. The application of such high heat resistant Al alloys for intake valves is a real innovation. The improved thermal conductivity leads to a significant reduction of temperature in comparison to steel valves.



a) components [Mahle] b) properties in comparison [PEAK Werkstoff GmbH]

Fig. 2 Valves made from AlSi17Fe7Ni2 (spray-formed)

The additives - The Co based materials with the following additional elements

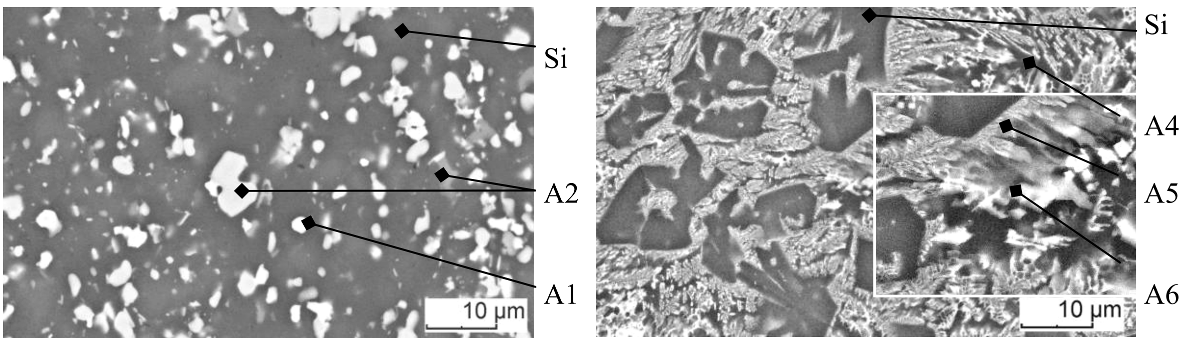
- Co-a: Co – Cr28-Mo5-Fe4-Ni3-Si1
- Co-b: Co – Cr25-Mo8-W10

used for EB alloying were selected based on a component-specific stress analysis and the basic material was taken into consideration. Regarding the present investigation the pre-deposition of the additional material was carried out by an axially symmetric sinter ring (Figure 1c). This method provides technical and technological prerequisites. Among others, it provides for a precisely defined additive amount and surface for energy coupling, the implementation of economically efficient multi-spot techniques (Figure 1b) and a reliable and fast deposition process for intricate component geometries.

4. Results and discussion

4.1 EB remelting

The primary silicon precipitates (Si_P) of the base material have a great importance in connection with EB liquid phase processes. Although the cooling rates for the spray-compacting process and for the EB remelting treatment are comparable, the primary silicon precipitates in the EB remelted layers become a little bit coarser (Fig. 3b). The higher the silicon level of the initial alloy, the greater the mean Si_P particle diameter, both in the initial (2…8 µm) and in the remelted microstructure (4…35 µm).



EDX [wt.%]	A1	Al 56, Ni 23, Cu 20
	A2	Al 59, Ni 36, Cu 3
XRD	Ni; Al_3Ni_2; Al_3Ni; Ni_3Ti; Al_7Cu_4Ni	

EDX: [wt.%]	A4	Al 77, Si 12, Ni 8, Cu 3
	A5	Al 70, Cu 16, Ni 7, Si 6
	A6	Al 65, Ni 14, Si 11, Cu 8, Ti
XRD	Al_3Ni_2; Al_3Ni; Ni_3Ti; $(Ni_{31}Si_{12})$	

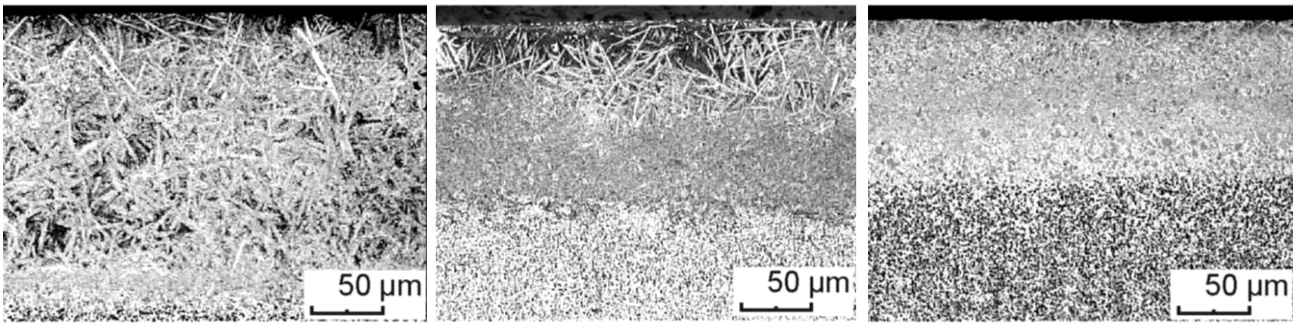
Fig. 3 Influence of EB remelting on the microstructure of base material (alloy 2)

Compared to the initial state of spray-formed materials, the process of EB remelting leads to the following changes concerning microstructure:

- formation of typical dendritic cast structure, i.e. dendritic precipitation of a part of the primary silicon (10…70%) over the base material (100%) with oversaturation of Al solid solution
- morphological change of intermetallic compounds
- formation of different intermetallic or metastable phases (e. g. needle-like Fe phases)

The needle-like Fe phases (seen in Fig. 4a) mentioned above are very critical with regard to technical applications, especially thermo-mechanical loading. A very fine remelted microstructure with fitting temperature-time-cycle (Figure 4b, c) was achieved.

Depending on the initial heat treatment state – F, T4 (120…200HV0.10) an increase of 20-60% in hardness (200…250HV0.10, see Figure 7c) of the EB remelted layer is observed.

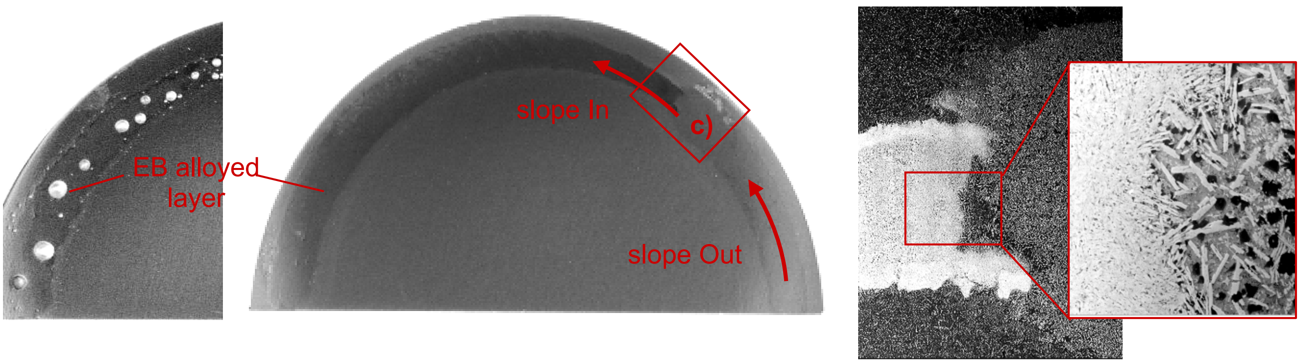


cooling rate increase →

Fig. 4 EB remelted microstructure after different temperature-time-cycle (alloy 1)

4.2 EB alloying

The additives (sinter ring) were EB remelted together with the surrounding valve material and an alloying layer (Figure 1d) was produced using the mixed process of three rotating beam spots. After one EB alloying treatment, great differences in microstructure and properties exist between the slope in and slope out area. A homogenous layer with optimized slope parameters was achieved for the whole area after continual remelting for two or three times.



a) alloy 1 b) alloy 2 c) microstructure (slope in and out)

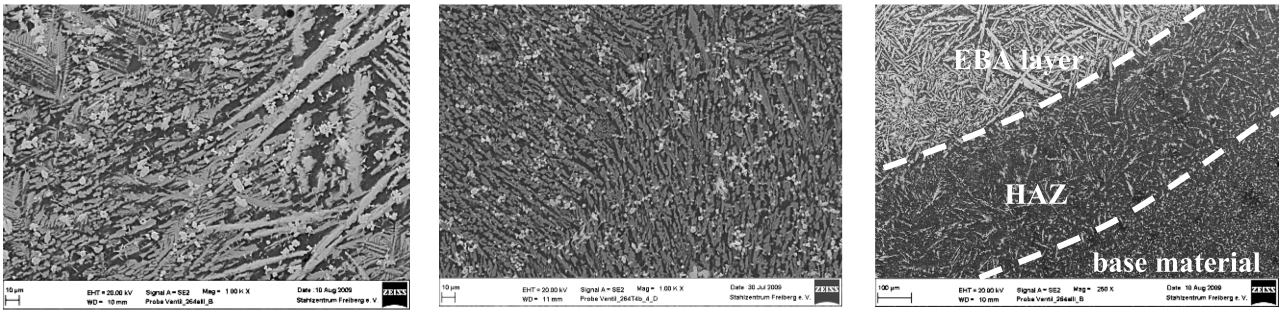
Fig. 5 EB alloying layer (top view)

The premise valid for all examined samples is to produce crack-free layers without pores. The latter is given only in case of the alloy 2 base material (Figure 5a, b) without any additional technological measurements. Results of this base material will be described subsequently.

This strongly limits the otherwise very large variation range with regard to adjustable chemical composition, microstructure and properties. In addition to the factors mentioned, it is above all the produced layer volume and/or the layer density which determine the technically usable layer hardness range (300…800 HV0.10). The dimension of the alloyed layer (cross section) depends on the energy that is deposited (spot size, beam velocity, beam current …). The concentration of additional alloying elements in the layer and also its hardness are a result of the sinter ring volume (dimension) and the fraction volume of the remelted (surrounding) spray-formed base material. The higher the portion of additional material added by EB alloying, the higher is the layer hardness.

Depending on the additive used (Co-a or Co-b), the EB alloyed layers show different structure formations despite comparable portions of additional alloys (Figure 6a, b). However, this does not influence the hardness of the layer (approx. 450HV0.10).

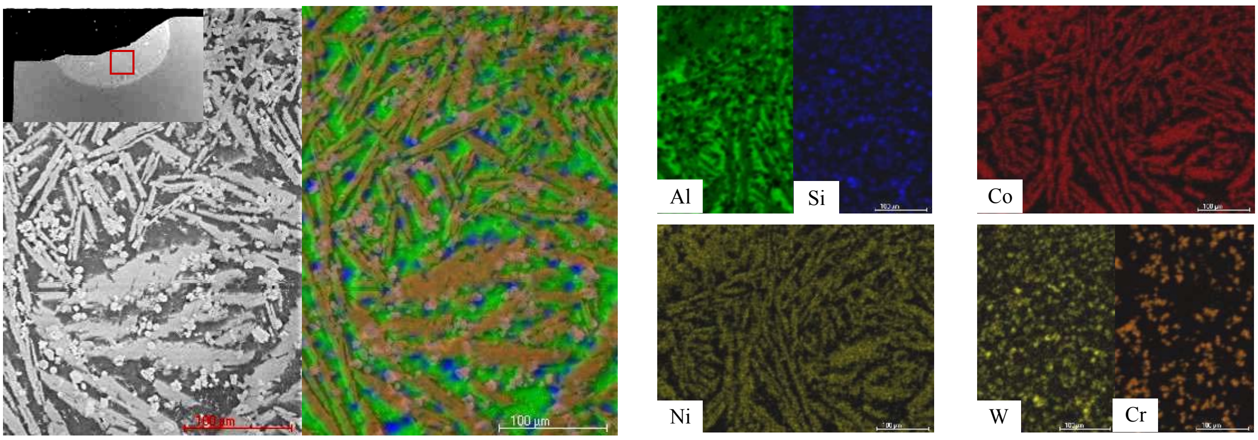
Under the alloyed layer a small (0.2…0.4 mm) heat affected zone (HAZ) with a remelted microstructure and improved hardness (see chapter 4.1) exists (Figure 6c).



a) EB alloyed Co-a b) EB alloyed Co-b c) heat affected zone

Fig. 6 EB alloyed layer with different additives (base materials: alloy 2

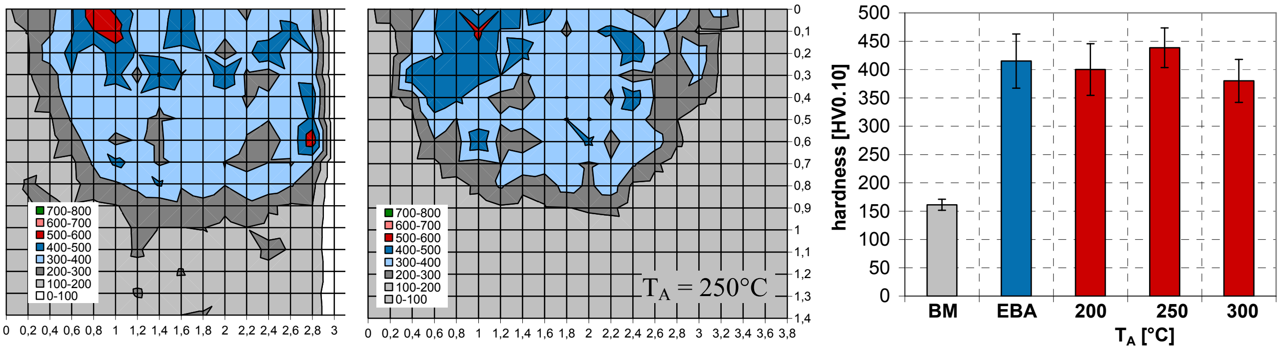
Figure 7a exemplarily shows the microstructure of an EB alloyed layer without cracks and pores and with acceptable hardness of about 450 HV0.10 (Figure 7a). As a result of the optimized EB technology, the distribution of deposited and alloyed additives is relatively homogenous inside the EB alloyed zone. The alloyed microstructure (Figure 6a on the right, b) consists of oversaturated Al solid solution (green), Si_P particles with a diameter < 20 µm (blue), elongate Co and Ni containing compounds (red, yellow) and finely dispersed W and Cr containing compounds.



a) EDX analysis of EB alloyed microstructure b) distribution of each element (colour)

Fig. 7 EB alloyed layer with Co additive (alloy 2)

The real loading conditions of intake valves are in the range of 150 to 250 °C. Therefore, the thermal resistance of the EB alloyed layers (EBA) with respect to the base material (BM) was tested at annealing temperatures (T_A) of 200, 250 and 300 °C for 24 h. EB alloying and annealing at these temperatures tends to influence layer hardness marginally (Figure 8c) considering the dispersion of hardness values measured afterwards (Figure 8a, b). A detailed evaluation of the microstructure is relatively difficult because of morphology differences (Figure 7a) inside the EB alloyed layer (e.g. centre, boundary) that depend on the cooling rate.



a) after EB alloying b) after EB alloying and annealing c) micro hardness of different states

Fig. 8 Hardness distribution of EB alloyed layer with Co additive (alloy 2)

5. Conclusion

In order to extend the use of aluminium alloys for components, especially in the automotive industry, it is necessary to protect functional surface areas of tribological systems against wear and/or corrosion. The use of EB allows to implement a precisely defined energy input. Thus, a locally defined treatment of the functional surface areas without or with only a small heat-affected zone, i.e. without any significant change of the base material properties, can be achieved.

For these purposes, EB surface treatment technologies without and with additional material deposition (remelting, alloying with Co) were developed and tested. By investigating several spray-formed Al alloys, the effect of different EB technologies and parameters on the quality and properties of the layer in connection with a special beam deflection technique (multi-spot) has been demonstrated. In the case of EB alloying, layers free of cracks and pores with a hardness of 450HV0.10 can be produced. The layer matrix compounds are characterised with regard to their macroscopic properties, microstructure and properties. It can be expected that more fields of application will be established for EB surface technologies within the coming years, notably in motor vehicle manufacturing and in the aerospace industry.

Acknowledgements

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