Stellite bearings for liquid Zn-/Al-Systems with advanced chemical and physical properties by Mechanical Alloying and Standard-PM-Route

Part I

[1]H. Zoz, [1]H.U.Benz, [2]K. Hüttebräucker, [3]L. Furken, [1]H. Ren, [1]R. Reichardt

[1]Zoz GmbH, D-57482 Wenden, Germany

[2]Thyssen Krupp Stahl AG, D-47161 Duisburg, Germany

[3]Thyssen Krupp Stahl AG, D-57204 Kreuztal, Germany

abstract

An important business-field of world-wide steel-industry is the coating of thin metal-sheets with zinc, zinc-aluminum and aluminum based materials. These products mostly go into automotive industry, in particular for the car-body, into building and construction industry as well as household appliances.
Due to mass-production, the processing is done in large continuously operating plants where the mostly cold-rolled metal-strip as the substrate is handled in coils up to 40 tons unwind before and rolled up again after passing the processing plant which includes cleaning, annealing, hot-dip galvanizing / aluminizing and chemical treatment.

In the liquid Zn, Zn-Al, Al-Zn and Al-Si bathes a combined action of corrosion and wear under high temperature and high stress onto the transfer components (rolls) accounts for major economic losses. Most critical here are the bearing systems of these rolls operating in the liquid system. Rolls in liquid system can not be avoided as they are needed to transfer the steel-strip into and out of the crucible.

Since several years, ceramic roller bearings are tested here, however, in particular due to uncontrollable slag-impurities within the hot bath, slide bearings are still expected to be of a higher potential.
The today's state of the art is the application of slide bearings based on Stellite® against Stellite which is in general a 50-60 wt% Co-matrix with incorporated Cr- and W-carbides and other composites.

Indeed Stellite is used as the bearing-material as of it's chemical properties (does not go into solution), the physical properties in particular with poor lubricating properties are not satisfying at all. To increase the sliding behavior in the bearing system, about 0.15-0.2 wt% of lead has been added into the hot-bath in the past. Due to environmental regulations, this had to be reduced dramatically. This together with the heavily increasing production rates expressed by increased velocity of the substrate-steel-band up to 200 m/min and increased tractate power up to 10 tons in modern plants, leads to life times of the bearings of a few up to several days only.

To improve this situation, the Mechanical Alloying (MA) technique is used to produce advanced Stellite-based bearing materials. A lubricating phase is introduced into Stellite-powder-material by MA, the composite-powder-particles are coated by High Energy Milling (HEM) in order to produce bearing-bushes of approximately 12 kg by Sintering, Liquid Phase Sintering (LPS) and Hot Isostatic Pressing (HIP).
The chemical and physical behavior of samples as well as the bearing systems in the hot galvanizing / aluminizing plant are discussed. Dependencies like lubricant material and composite, LPS-binder and composite, particle shape and PM-route with respect to achievable density, (temperature-) shock-resistibility and corrosive-wear behavior will be described.
The materials are characterized by particle size analysis (laser diffraction), scanning electron microscopy and X-ray diffraction, corrosive-wear behavior is determined using a special cylinder-in-bush apparatus (CIBA) as well as field-test in real production condition.
Part I of this work describes the initial testing phase where different sample materials are produced, characterized, consolidated and tested in the CIBA under a common Al-Zn-system. The results are discussed and the material-system for the large components to be produced for the field test in real production condition is decided.

1. Introduction

The present paper is a summary of Part I of the cooperative project 09-2-7223 of Zoz GmbH and Thyssen Krupp Stahl AG in Germany.
The aim of this work is to replace common bearing-systems for hot-dip galvanizing/aluminizing plants operating in the liquid system (here Zn, Zn-Al and Al-Zn, future target Al) by using advanced material and advanced design-technique to produce some of the bearing components.
Since the huge and complicated coil-coating systems are very sensitive to major changing, a philosophy of small and single steps has been preferred.
First only the consolidation technique of the well known and proved material for galvanizing plants is changed from casting and welding to Hot Isostatic Pressing (HIP) which itself promises advantages regarding wear-behavior and major advantages regarding loss by damage due to a much better and unique structure and in particular a full dense bulk-material without failures and cracks [1].
Additionally the Mechanical Alloying technique (MA) [2-4] is applied to improve in particular the mechanical properties of the material by alloying a lubricating material highly dispersed in the base- and standard-material matrix.
Within this procedure also High Energy Milling (HEM) [5] is used to effect the materials structure before consolidation as well as Liquid Phase Sintering (LPS) [5-7] under HIP related to the used alloying-component.
The next major step is the transfer of the won experience, knowledge and results to the more difficult as less understood aluminizing plants where today different materials are used with tremendously shorter cycle times.
The final target as of today results in the submitted CRAFT-project 1999-70229 where the bearing material and the components shall completely be changed to ceramic- and probably carbon-base.

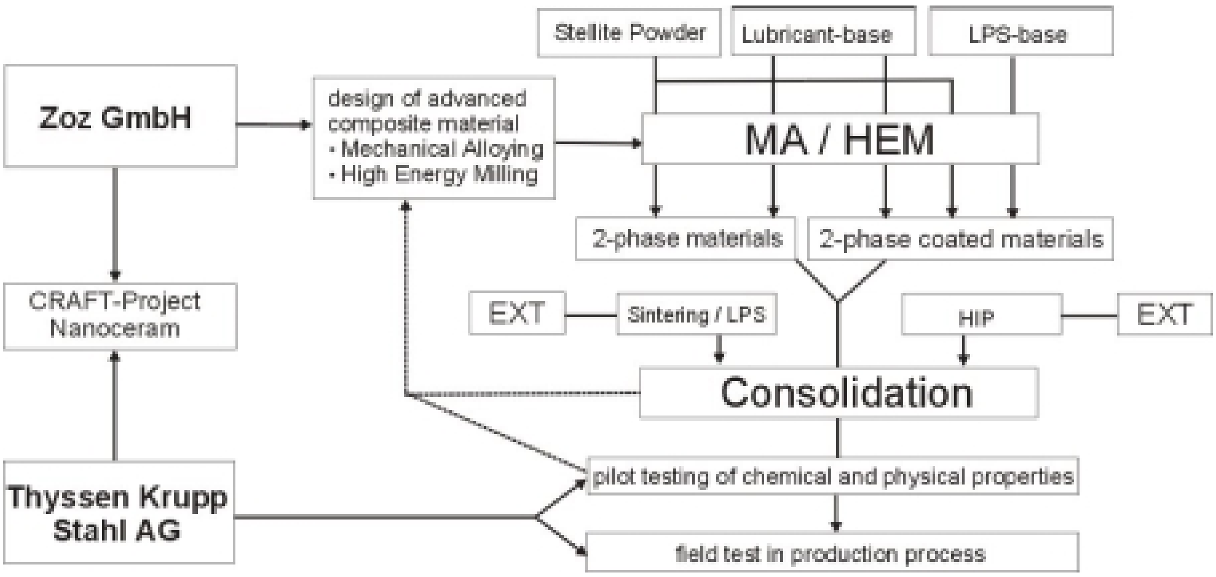


Fig. 01: flow-chart of Cooperative Project 09-2-7223

2. State of the art of bearing systems in hot dip galvanizing / aluminizing plants, applications

Most frequent applications of Zn/Al coil-coated metal-strip are today found in automotive, building and construction as well as household appliances. Figure 02 shows coated coils where the net-weight is up to 40 tons as well as some examples of finished parts:

Fig. 02: coated metal-strip coils and commercial applications

A common hot-dip galvanizing/aluminizing system is a large continuously operating plant where the mostly cold-rolled metal-strip as the substrate is handled in coils up to 40 tons unwind before and rolled up again after passing the processing plant which includes cleaning, annealing, hot-dip galvanizing / aluminizing and chemical treatment (*Figure 03*). The here only part of interest is the transfer-system for the metal-strip located in the crucible of the hot part. The crucible with dimensions in several-meter-range carries the liquid metal for coating where the transfer system is dumped into the crucible and molten metal.

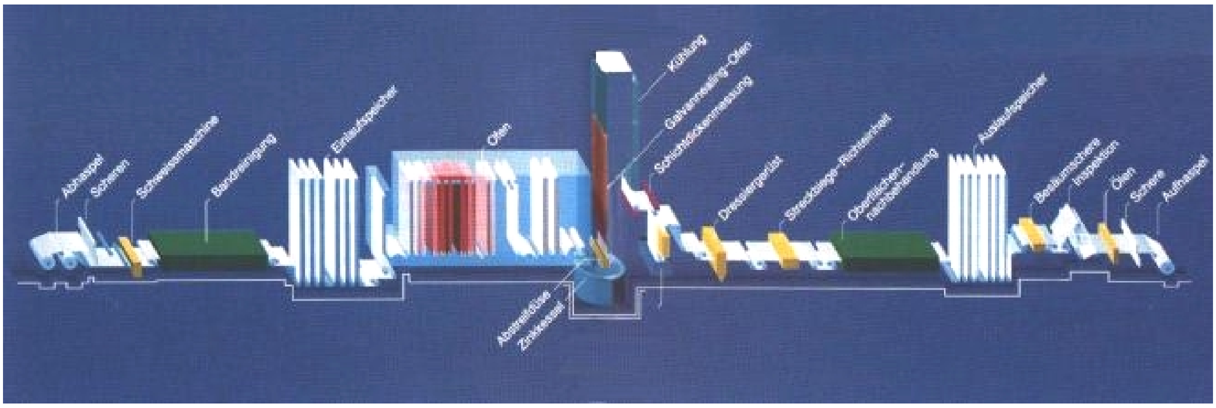


Fig. 03: hot-dip galvanizing/aluminizing plant

The transfer system in principle must carry one pot-roll which diverts the metal-strip inside the crucible to run in and out in approximately vertical position. In fact always a second and smaller stabilizing roll as well as often a third (also stabilizing) roll is used (*Figure 04*).

The dimensions of the rolls depend on the to be coated metal-strip where the length refers to the width of the strip in a range of 400-2000 mm. The diameter of the pot-roll refers to the thickness of the metal strip and starts approximately at 600 mm for thin strip up to 2 mm ranging to 1500 mm for thick strip up to 5 mm.

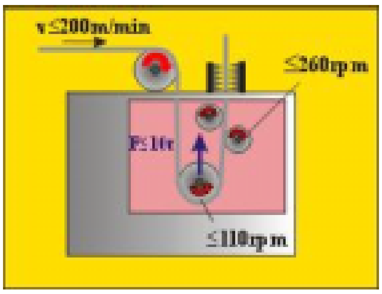


Fig. 04: transfer system inside the crucible of a hot-dip galvanizing/aluminizing plant

The major physical operating criteria with respect to the bearing of the pot- and stabilizing rolls are the velocity of the metal-strip resulting into the slide-velocity at the bearing-components as well as the tractate power of the metal strip related to the thickness of the metal-strip and resulting into the pressure between the bearing components.
The main chemical criteria is the composition of the galvanizing/aluminizing bath resulting in the operation temperature of the bath (*Figure 05*) as well as the preheating level of the metal-strip.

	bath-type	composition	operation temp.	bearing dynamic		bearing static	
01	Zinc	Zn	450-500ºC	S B	stellite & gradient stellite & gradient	S B	stellite, zirconia stellite, zirconia
02	Galvan	Zn-5Al	450-500ºC	S B	stellite & gradient stellite & gradient	S B	zirconia stellite, zirconia
03	Galvalume	Al-45Zn	ca. 600ºC	S B	stellite & gradient stellite & gradient	S B	zirconia stellite, zirconia
04	Aluminium	Al-10Si-3Fe	ca. 700ºC	S B	100Cr6 Cf70	S B	stellite zirconia

Fig. 05: common bearing-systems, cycle time & bath-composition of hot-dip galvanizing and aluminizing plants

The pot-roll (*Figure 06*) almost only carries the tractate power and is therefore the more critical component with respect to wear resulting in the possible cycle time. The stabilizing rolls (*Figure 07*) do operate at higher velocity due to the smaller diameter but based on experience a minor subject to wear regarding their bearings.


Fig. 06: pot-roll


Fig. 07: stabilizing-roll

The common bearing systems are based on a cylindrical bearing-bush (fixed on the rolls) sliding in a bearing-bush (semicircle or full, fixed on the transfer-unit). Up to the Al-rich Galvalume-system, most frequently used bearing material for both parties is Stellite® where the average compositions are listed below:

	C	Cr	W	Nb	Co	specifications
Stellite 4	1,0	33,0	14,0	--	rest	steelkey
Stellite 6	1,0	26,0	5,0	6,0	rest	steelkey
Stellite 12	1,80	29,0	9,0	--	rest	steelkey

specifications in weight-%


Fig. 08: caste and machined bearing components

The bearing components to be fixed on the rolls are either consolidated by casting as a full stellite bulk (*Figure 08*) or welding (*Figure 09*) if a gradient composite must serve extremely high shock-resistibility for the transfer system [8].


Fig. 09: welded and machined bearing component

The gradient composite materials by welding have the advantage that fixing to the roll can be achieved by welding the though base-material which is usually similar to the base material of the roll itself (see *Figure 05*). The full-bulk-casting is the cheaper technique.
The counter-bearing components (fixed at the transfer-system-frame) are either made by casting stellite (*Figure 10*) or zirconia stabilized [9] with a metal oxide by isostatic pressing and sintering or slip-casting and sintering (*Figure 11*).

Fig. 10: caste stellite bearing component

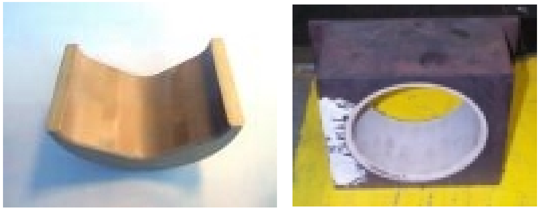


Fig. 11: sintered zirconia bearing components

3. to be used technique: Advanced Materials by Mechanical Alloying, Principle and General Applications

During the last decades the Mechanical Alloying technique (MA) [2-4] has been found to be very effective in producing powders with interesting properties. By this means it is possible to synthesize alloys or composite materials with highly dispersed components [10] far away from thermal equilibrium state like amorphous or nanocrystalline materials [11, 12]. Furthermore, the powder route is a way to combine elemental or pre-alloyed components to materials which are generally not receivable by conventional processing techniques due to e.g. the immiscibility of their components.

Mechanical Alloying often leads to material transformation of the crystalline structure by solid state reactions. The Gibbs´ free energy is increased to higher levels during milling and results in reactions of a lower metastable or stable state. The interaction between milling balls and powder particles can be characterized by processes like cold-welding, plastic deformation and further fragmentation of the particles. Atomic dislocations, a high defect structure of the lattice, the immense magnification of the boundary surface and a high diffusion rate leads to low activation energies for those reactions.
If the same technique is applied for particle size reduction [5] and / or particle deformation [13, 14] of single-systems to receive a special particle geometry (e.g. flakes of ductile metals), this route is better described as High Energy (ball) Milling (HEM).
The definition of Reactive Milling (RM) is suitable if during milling a chemical reaction is wanted and observed. The advantage here can be an ultra-fine (nanoscaled) dispersion of particles/grains in a matrix and sometimes cost saving due to a cheaper starting material [10].
The following table gives most important applications of High Energy Milling, Mechanical Alloying and Reactive Milling in survey:

Applications, Products		
Surface, Shape, Particle Size (geometry)	**Alloy (pseudo)**	**Reactive Milling**
• Flakes (Particle Deformed Powder)	• Nanocrystalline Materials	• Contact Material
• Particle Coating (LPS, S)	• Amorphous Materials	• Nanocrystalline Materials
• Nanocrystalline Materials	• Oxide Dispersion Strengthened Alloys	• Mechanochemistry
• Highly Dispersed Phased Materials	• Iron and Oxide based Magnetic Materials	• Solid state synthesis
• Soft Magnetics	• Bearing Materials containing Solid Lubricants	• Hydride - Dehydride
• Particle size reduction (e.g. Enamel)	• Ceramic Metal Composites (MMC, CMC, MMC, CCC)	• Activation (Catalysts)

Table 12: applications / products of Mechanical Alloying, High Energy Milling and Reactive Milling

Mechanical Alloying has been described as a process where powder particles are treated by repeated deformation, fracture and welding by highly energetic collisions of grinding media in a milling process. High Energy and Reactive Milling is performed by the same processing principle where the variation is in general based on the target of processing, the transformation effect of kinetic and the starting materials.

The various procedures can be described as High Kinetic Processing (HKP) where the collision of grinding media is the main event of kinetic energy transfer from the milling tools into the powder [5, 15].

Figure 13 shows the schematic of the collision. The basic equation for the kinetic energy in dependency of mass and velocity $E_{kin} = ½\ m\ v^2$ leads to the conclusion that the maximum relative velocity of grinding media is the most determining factor is the in the process.

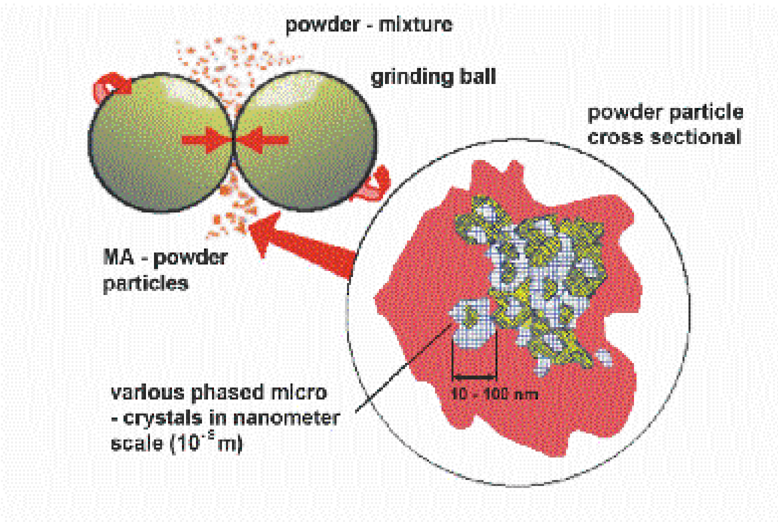


Fig. 13: schematic of collision, principle of HKP

4. the lubricating function

The PM-consolidation route is considered to be certainly superior to casting and welding due to a unique bulk-structure and a full dense material. Inclusions and hollows (*Figure 14*) in the bearing material will not any longer be present at all. In particular cracks and micro-cracks cause major losses as they act as a diffusion speedway for the liquid metal. This is avoided by the application of HIP for consolidation.

Fig. 14: bearing bush of a pot-roll with open hollows and cracks after 1st level -machining

The general idea to apply MA/HEM is to introduce a lubricating function into the common base material where two principles (*Figure 15*) are considered and tested.
The first is to introduce an alloying element in particular with a lower ductility and better slide-behavior into the stellite-matrix. By this the wear behavior of the consolidated bearing is expected to be improved where the chemical properties at least within the cycle time is not expected to be negatively influenced as the consolidation route of HIP leads to a full dense packing. A fine and homogeneous distribution of the second phase will lead to a constant availability of solid lubricant in the wear system under operation. Due to diffusion reactions during powder processing (MA) as well as HIP, furthermore an excellent binding of the bulk-parts is expected.
Another idea is to coat the stellite-particles with the second phase which has naturally a far lower melting point than the stellite base. In this case the parameters for HIP are to be set to reach the liquid phase of the second phase during the holding time. This must lead to an excellent distribution of the second phase which actually creates a matrix itself and is expected to lead to an optimum of availability of solid lubricant in the wear system under operation.

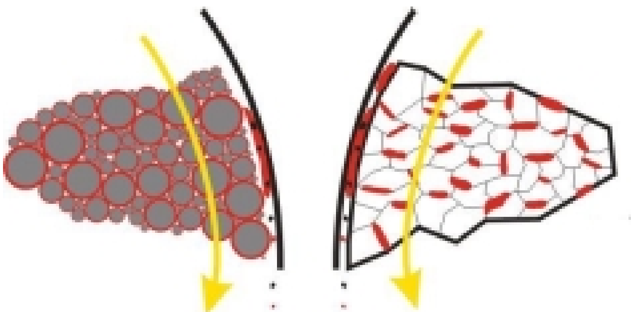


Fig. 15: lubricating function to be achieved by HKP

5. production of sample material, characterization

The lab-scale powder production for the to be consolidated samples for testing different material systems, 400g each of Stellite-4 powder was processed without and with two different alloying elements A+B under each 3 different parameter settings 1-3. The used device for HKP is a Simoloyer CM01-2l (*Figure 16*). In case of using alloying element B, a process control agent (PCA) had to be added. For consolidation the PCA had fully to be removed using a Zoz-vacuum-furnance-tube HR63-1 (*Figure 17*).

Fig. 16: Simoloyer CM01-2l

Fig. 17: Vacuum-Furnace-Tube HR63-1

The flow-chart as below gives an overview of 10 different sample materials that have been produced for consolidation.

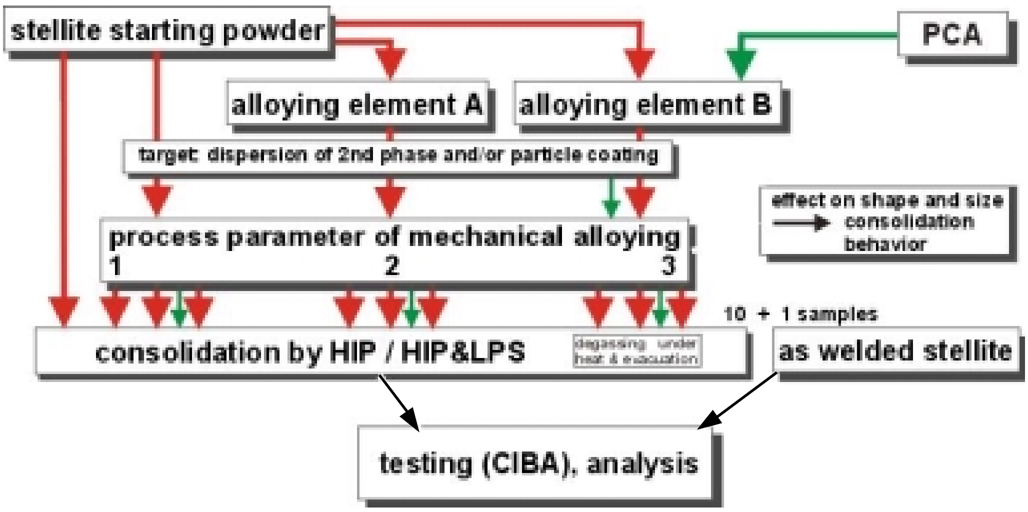
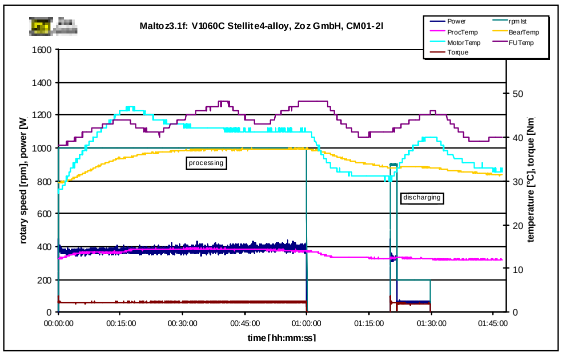


Fig. 18: flow-chart of powder production by HKP for the consolidation of 10 different samples

The base-operation-parameters in the Simoloyer CM01-2l were determined as follows:

parameter (Simoloyer® CM01)	
rotational speed/constant rotational speed/cycle operation	1000rpm/650rpm (only if PCA)
grinding media	Ø 5mm, 100Cr6
ball mass	2000g
powder mass	200g
atmosphere	air
cooling	water

Fig. 19: set base parameters of HKP-device (CM01-2l), alloy V1060C



In case of processing pure stellite-material as well as alloying element A, constant operation has been suitable, in case of alloying element B, Cycle Operation [16, 17] has been applied in order to avoid agglomeration during processing.

The starting base powder is a stellite 4 with a D50 of about 170 µ. The particle size distribution (*Figure 20*) had been investigated by laser diffraction using a Coulter LS200, the gas-atomized material has been observed under SEM (Figure 21) using a Philips XL-30 proving typical spherical shape.

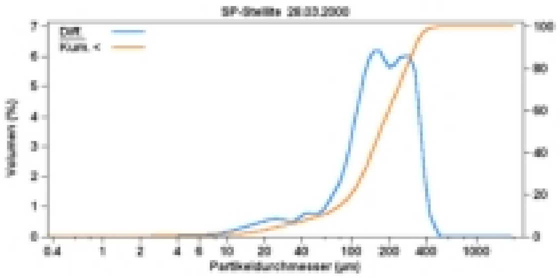


Fig. 20: particle size distribution

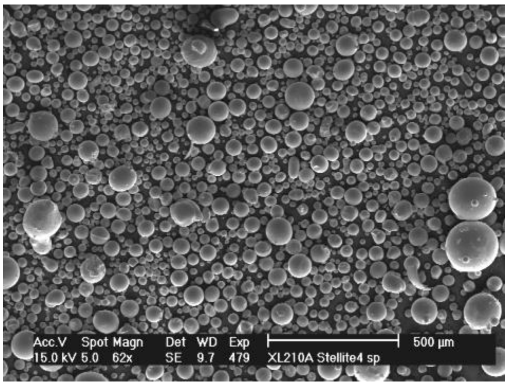


Fig. 21: SEM of stellite starting powder

The good chemical resistance as well as the high hardness of this material is based on the austenitic Co-matrix with embedded and thermodynamically stable Cr- and W-carbides.

After HKP, the powders were investigated again, where the evaluation over the parameter-setting is given for 2 selected materials PM09MA1A-C and PM09MA3A-C as follows:

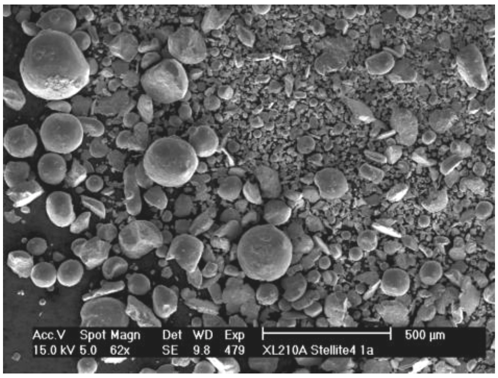


Fig. 22: SEM of PM09MA1A

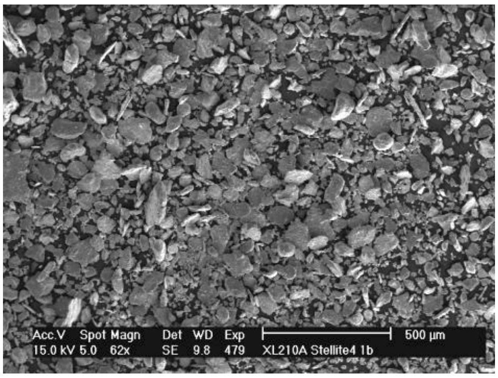


Fig. 23: SEM of PM09MA1B

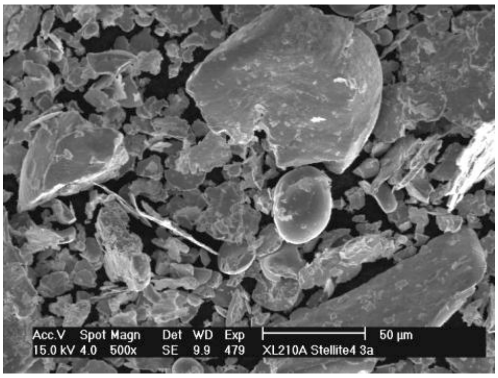


Fig. 24: SEM of PM09MA1C

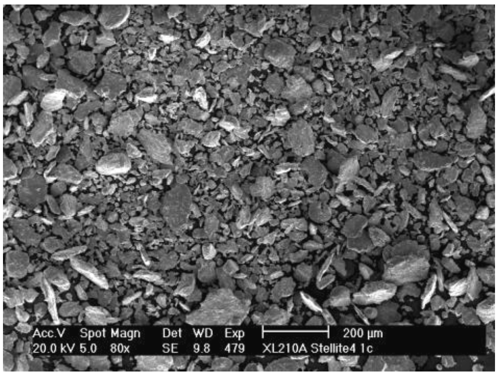


Fig. 25: SEM of PM09MA1A

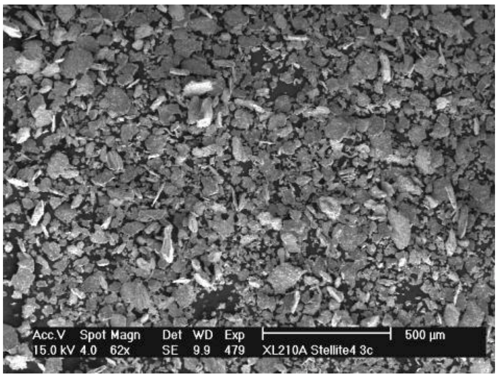


Fig. 26: SEM of PM09MA1B

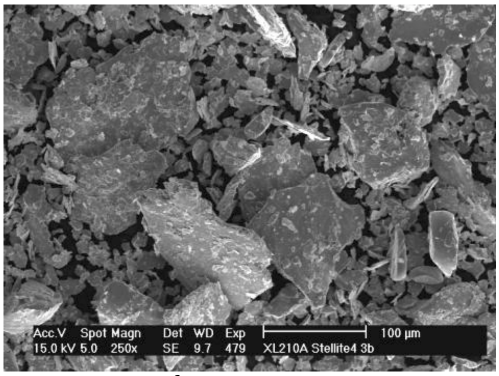


Fig. 27: SEM of PM09MA1C

The technique of particle-coating is exhibited by the following micrograph and XRD-pattern, where on the SEM the EDX-spot is marked and the XRD shows clearly not the peaks of stellite but those of alloying element B (*Figures 28 and 29*).

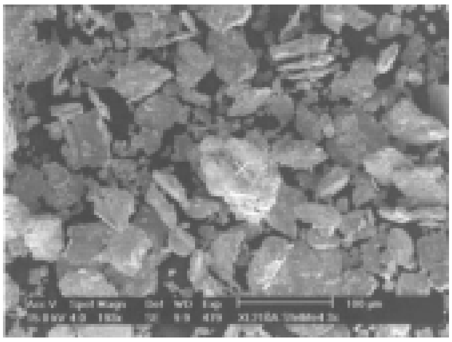


Fig. 28: SEM of PM09MA1C

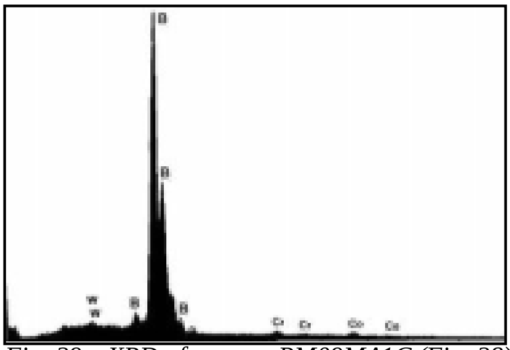
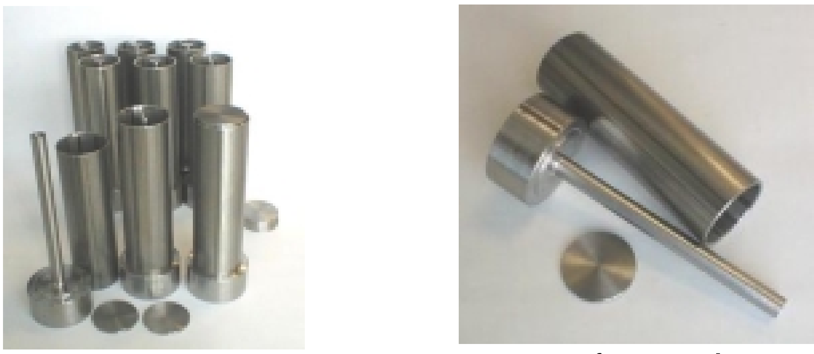


Fig. 29: XRD of spot on PM09MA1C (Fig. 28)

6. consolidation of samples by HIP and HIP/LPS

For the production of sample-bulk-parts, a design had been chosen that simulates the more complex gradient bush-system in later testing in CIBA (Cylinder In Bush Apparatus – simulation unit for hot-dip galvanizing) and characterization.

Therefore the powder containers for HIP were produced with an inside (center) cylinder, the tube and the closing-flange (*Figure 30*).



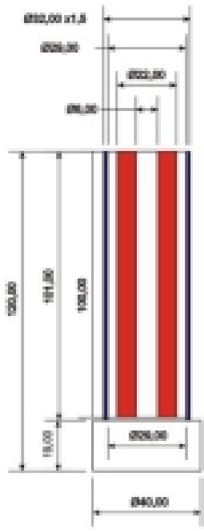


Fig. 30: container parts for HIP with center-cylinder

The produced 10 powder samples were canned into the HIP-containers, closed and evacuated. These 10 parts were then consolidated by HIP and LPS under HIP, using a ASEA 200-300 (Figure 31).

ASEA-Unit	
diameter [mm]	200
length [mm]	300
maximum temperature [°C]	2000
maximum pressure [MPa]	200

Fig. 31: HIP-device ASEA 200-300

A flow-graphic of the consolidation process is given as follows:

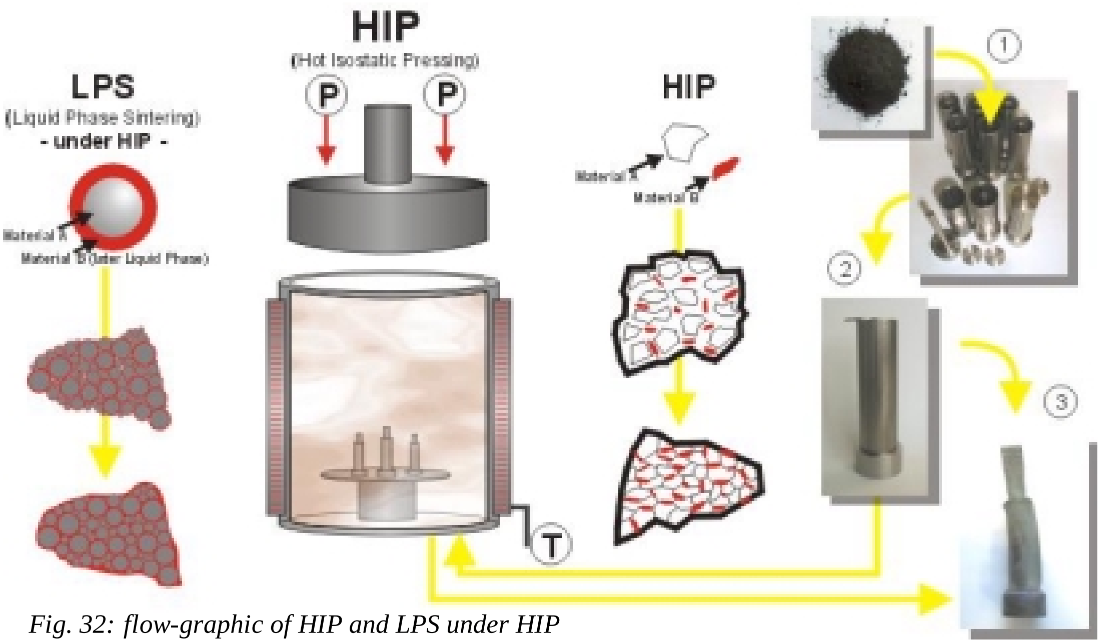


Fig. 32: flow-graphic of HIP and LPS under HIP

After consolidation, a variation of deformation behavior related to the different materials has been observed (*Figure 33*). Since the powder containers had equal dimensions, the reached maximum dimensions after machining give an expression for the different shrinkage of samples. In order to take consideration of striction and curvature, the final volume of machined samples had been calculated and is listed as follows (*Figure 34*):

Fig. 33: deformation behavior during consolidation by HIP and LPS under HIP

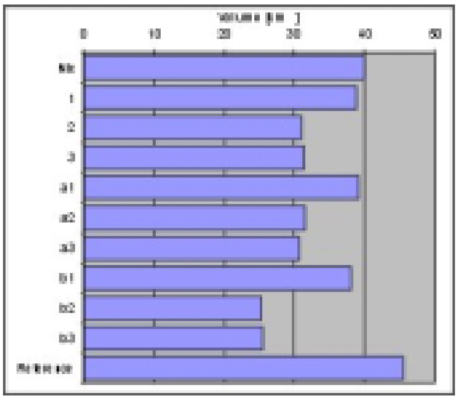


Fig. 34: deformation behavior expressed by maximum volume of samples after machining

The knowledge on the deformation behavior is important for the design of the real bearing components (part II), the explanation is certainly assumed to be in the deformation of powder material by HKP where the evaluation of a definite dependency needs further investigation and will be of major interest once the product (bearings) is introduced in the market as it sensitively effects the material (powder) consumption to produce a single bearing bush.

7. CIBA – simulation unit of a hot dip galvanizing / aluminizing plant

To evaluate the wear-behavior of the samples based on 10 new materials, a Cylinder In Bush Apparatus (CIBA) has been designed and produced (*Figure 35*).

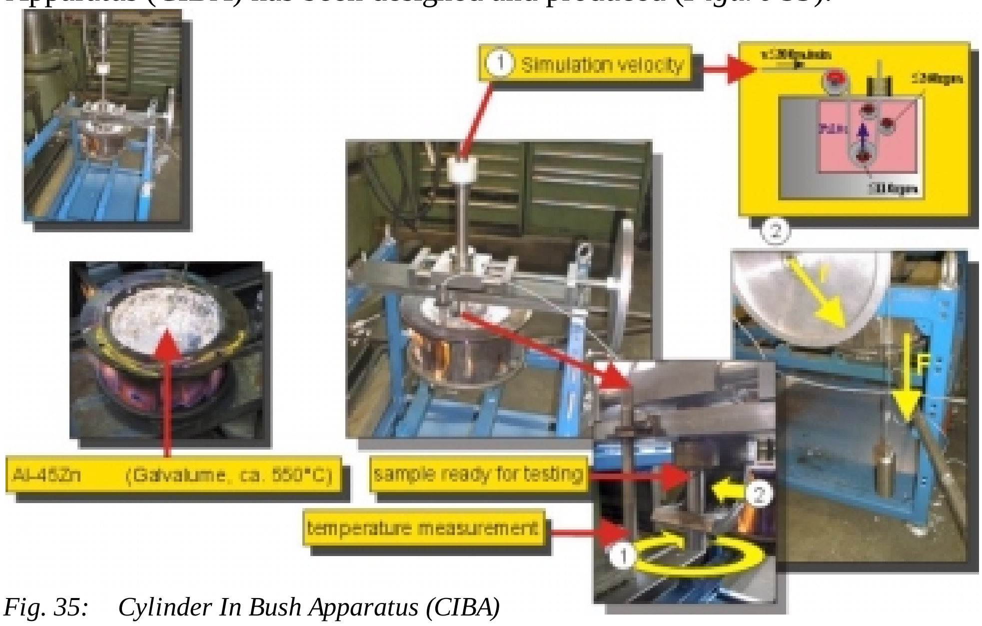


Fig. 35: Cylinder In Bush Apparatus (CIBA)

It allows to compare the new materials with the state of the art represented by a reference sample under simulated real condition. The reference sample has been produced by common welding-technique in the same dimensions as the new samples.

The main demands for CIBA are:

- Simulation of liquid metal bath
- Simulation of bearing system
- Simulation of tractate power
- Simulation of slide-velocity in bearing system

The **liquid metal bath** is simulated by real condition, a crucible of about 10 liters is used to supply the Al-45Zn-bath (Galvalume) at 550 °C where the temperature measurement and in particular the temperature supply by gas-heating did cause sensitive problems as described later.
The **inner part of the bearing system** (bush fixed on the rolls) is simulated by the bulk-sample itself (cylinder), carrying the new materials as well as the reference material. The **outer part of the bearing** (bush) is simulated by a real stellite counter-bearing part, where a corresponding hole had been drilled into the bearing in order to use this as the bush.
The **tractate power** is simulated by a transfer-unit on top of CIBA which ends on a gravity-load on a turning-wheel where the needed load is determined by calculating over the radius of the turning wheel, the transmission of the connecting-thread, the surface area of the bearing system as well as the mechanic inert resistance of the whole system determined by force measurement. The reference area of the bearing system in real condition could only and had been determined by observation of a used counter-bearing (*Figure 36*). The to be adjusted tractate-power then had been trippled.
The simulation of the **slide-velocity** in bearing system is supplied by the drive unit of CIBA where a drilling machine is connected to CIBA by the coupling at the drive-shaft. The rotational speed for testing has been calculated from the real system based on the known diameters.
The **temperature measurement** is supplied by a NiCr-Ni thermocouple with interface converter connected to a PC. A temperature control has been impossible, based on problems with heating/cooling as described later.
A **cooling system** for the main-bearing of CIBA had unexpectedly to be installed during testing and is based on simple air-flow.

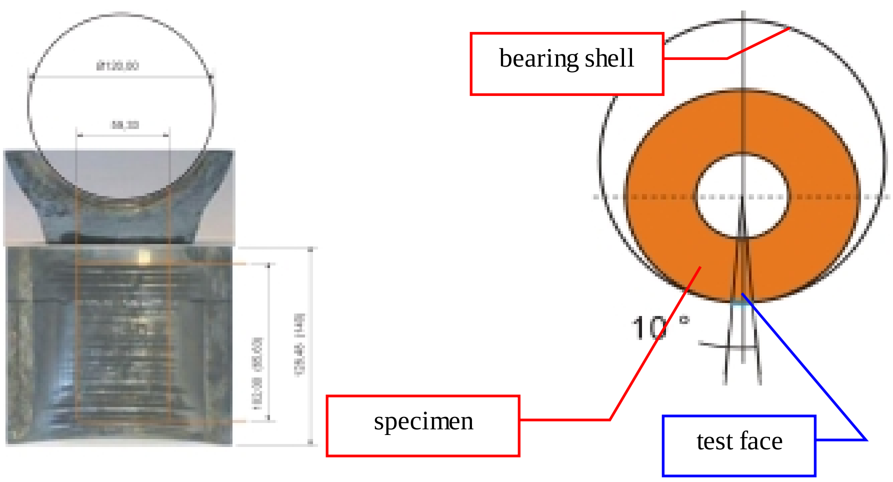


Fig. 36: used counter-bearing of galvanizing plant, determination of reference area

8. Testing of the consolidated samples results and characterization

The ten consolidated bulk-samples (*Figure 38*) as well as the reference sample have been tested in CIBA under the determined parameters as explained under 7. The main parameters are given as follows:

operation parameters	
velocity simulation	460 rpm
tractate simulation	1.5 kg
temperature	535-547°C
athmosphere	Air
bath	Al-45Zn
bush	Stellite
time	5-10 hours

Fig. 37: main parameters of testing in CIBA

After testing in CIBA, the samples had been removed (*Figure 39*) and the Galvalume-rest on the samples has been removed by acid. The samples have then been measured with respect to dimension and hardness. In fact the hardness-measurement was planed to be done before testing in CIBA but was not.

Fig. 38: sample after machining

Fig. 39: sample as removed from CIBA

The given chart of representative temperature curves during operation in CIBA (*Figure 40*) identifies temperature variation from 535 – 547 °C. In the given Al-Zn phase-diagram (*Figure 41*), this average is marked and shows that this data does not lead to a complete liquid system.
The gas heating system of CIBA was not found to be suitable for the needed temperature of 600 °C. The CIBA had to be operated always with maximum heating which also means that no temperature control has been possible. However the Galvalume-system must have been in liquid phase inside the test-bearing-system as the drive-shaft of CIBA always could be turned manually. This means that the maximum heating capacity of CIBA did lead to a stage, where the temperature gradient from the just a little (50 mm) outer position of temperature measurement ranged from semi-solid phase to liquid phase. In other words it is certainly assumed that the temperature inside the bearing must have been 30-50 °C higher that at the measurement-couple.
In particular due to the problematic heating, we have not been able to control and maintain the Galvalume-bath during operation where we certainly expect that a decomposition towards zinc has taken place due to slag-formation.
Additionally the thermal-isolation including a heat-shield on top of the crucible which can not be seen on the figures, has not been found suitable to prevent overheating of the bearing-system of CIBA itself. This might of course have occurred also by temperature-flow via

sample and drive-shaft. Finally this had to be solved by an air-flow-cooling system on top of CIBA. As a consequence, the bearings of the drive-shaft of CIBA have been restored preventive after every single sample-testing.
However and taking into consideration all above problems we do not believe at all, that these problems can cause tremendous relative change in the to be drawn results as they are not based on absolute data but on relative data to the reference sample. In any case part ii, the field-test will prove this or not.

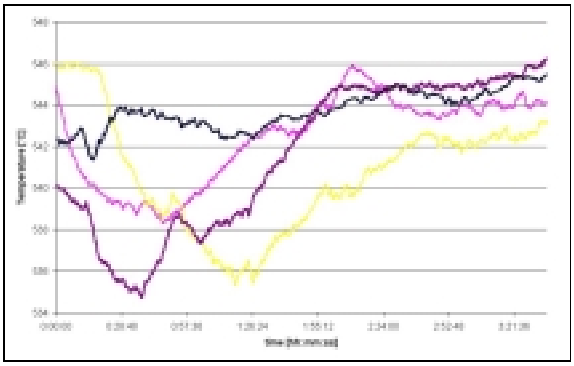


Fig. 40: representative temperature curves

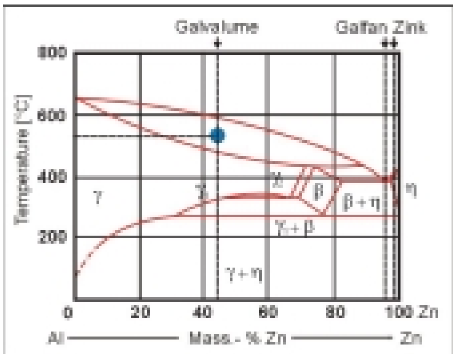


Fig. 41: Al-Zn phase diagram

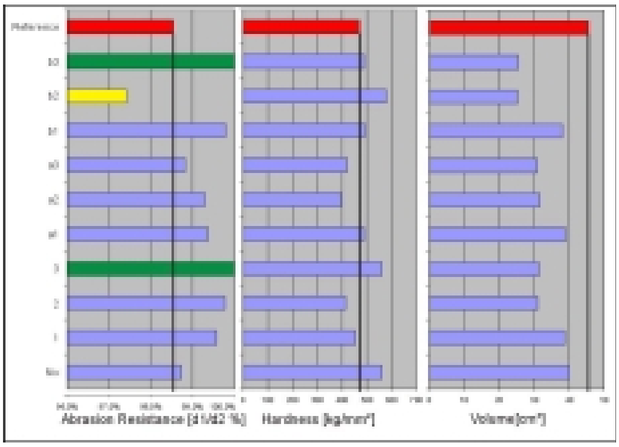


Fig. 42: comparison of measurement results

The following diagrams (*Figure 42*) show the comparison of measurement results of abrasion resistance and hardness after testing in CIBA as well as the cylinder-volume of samples after machining.

Most important here is the comparison of the abrasion resistance of the 10 new materials with the reference material. The data is given in negative-percentage expression which means the higher the value, the lower the abrasion.

Except of sample b2, all new materials show a better behavior than the reference ! This proves that the PM-route in general is superior to the common consolidation technique.
Up to now there is no explanation for the surprising fall-out of sample b2. The metalographic characterization of the cross-section of the consolidated samples is expected to give further clearance here but is not done yet. Following the line-up of sample 1-3 and b1-b3, we assume that b2 is a loss for a right now unknown mistake in the procedure. In any case 3 and b3 show a significant superior to all other and in particular to the reference. In fact no significant loss of material by abrasion could be obtained, which means that the value of 100 % might be maintained also in longer operation.
A dependency between hardness and abrasion resistance can not be observed, which might carefully be considered as a hint that next to better consolidation with a better structure of the material, also a lubricating function really plays a role. But up to now this can not be proved, this might be proved by metalographic observation in the next parts of this work.

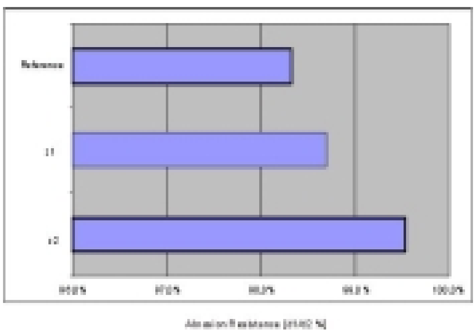
A slightly dependency between hardness and shrinkage can be observed and can only be caused by HKP and composition. In particular a dependency between deformation of powder particles and shrinkage during consolidation can be assumed as due to the design of the powder containers with the inner cylinder only tapping before closing and evacuating could be applied.
The carefully observation of samples before and after testing has shown that all samples consolidated by PM-route did not show any cracks, inclusions or hollows. Also no failures with respect to the diffusion-zone between inner cylinder and consolidated material could be noticed. In other words it has been possible after a correct determination of the base material for the inner cylinder related to the heat-expansion-coefficient of the whole system as well as the chemical properties against the liquid metal, to create a good and stable binding of two completely different material-systems by HIP- respectively LPS/HIP-consolidation itself. This result is important, as it shows not only the potential of a better gradient-bulk-material but also the potential of lower producing cost compared to the welding-technique.

All samples made by PM did not show either in the testing-zone nor in the non-testing zone inside the bath any effects of chemical reaction or erosion by diffusion due to the contact with the liquid Galvalume. Since the chosen alloying elements in single phase would immediately go into solution with the liquid metal bath, this proves that the new way of material-production including MA, HEM, LPS and HIP allow to produce materials with better physical properties maintaining the good chemical behavior of the stellite-base.

9. Determination of the to be used material system for field test in the galvanizing / aluminizing plant

Since the results of 8. give not a single best material but a choice of two where only the minimum superiority to the reference material is given equal for both, another operation series of the materials 3, b3 and the reference material under extended condition has been performed.

The results given as follows (Figure 43) conclude that the system Z1 is the to be preferred one and that it shows in total a superior abrasion resistance of approximately 20% to the reference material.



Finally the material-system Z1 is chosen to be the candidate for part II of this work where 2 set of mechanically alloyed bearing bushes with a weight of approximately 12 kg each are produced and tested under real condition in two different hot-dip-galvanizing plants, one set (single-bulk) in the zinc-rich bath at Thyssen in Ferndorf and the other set (gradient-bulk) in the aluminum-rich bath at Thyssen in Eichen.

Fig. 43: comparison of measurement results (second trial with 3, b3 and reference only)

10. Conclusions, Outlook, Acknowledgement & References

Summary

The state of the art of bearing systems under liquid metal in large hot dip galvanizing / aluminizing plants has been shown.
The principle of Mechanical Alloying has been explained, examples of potential and realized applications have been given.
It has been explained how Mechanical Alloying shall be used to introduce a second (lubricating) phase into the chemical resistant Stellite-base-material in order to improve the physical properties expressed by the cycle-time of the bearing-system in the liquid metal.
The alternatively/additional route, the coating of powder-materials in order to apply Liquid Phase Sintering (LPS) during consolidation has been shown, too.
The production of 10 sample parts, different with respect to material and process-parameters, by Hot Isostatic Pressing, by Mechanical Alloying and HIP as well as by MA and LPS under HIP has been described. Different consolidation behavior represented by different shrinkage has been observed and listed in result of achievable volume after machining the samples.
The Cylinder In Bush Apparatus (CIBA), a device to simulate the operating condition with respect to steel-strip velocity and tractate power has been explained and applied to (wear-)test the 11 samples in real-like condition.
The results of wear-test in CIBA of the 10 samples and one reference sample have been compared with respect to material-loss-, shrinkage- and hardness-relation.

Results

The experiments have shown that all of the 10 PM-samples show better wear resistibility than the conventional reference sample (except sample 2b which is regarded as a failure here).
A dependency between hardness and abrasion resistance can not be observed, which might be a hint that next to better consolidation with a better structure of the material, also a lubricating function really plays a role (metalographic study necessary).
The PM-samples did not show any cracks, inclusions, hollows or binding failures in the diffusion-zone between inner cylinder and consolidated material.
It has been possible to create a good and stable binding of two completely different material-systems by HIP- respectively LPS/HIP-consolidation itself.
All PM-samples did not any effects of chemical reaction or erosion by diffusion in the liquid metal.
The given new way of material-production including MA, HEM, LPS and HIP allows to produce materials with a 20% improved abrasion resistibility but maintaining the good chemical behavior of the stellite-base.

Outlook

Part II of this work will describe the field test in a hot-dip-galvanizing/aluminizing plant of the mechanically alloyed bearing bushes under aluminum-rich liquid metal. After testing, the bushes will be characterized and obtained results with respect to wear, expected lifetime, surface roughness and infiltration will be discussed.
Part III of this project will describe a second initial testing phase where the won results of part I+II will be transferred to the Al-Si system.
Part IV of this project will describe the field test in a hot-dip-aluminizing plant of the mechanically alloyed bearing bushes under aluminum liquid metal. After testing, the bushes will be characterized and obtained results with respect to wear, expected lifetime, surface roughness and infiltration will be discussed.

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