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Dry strip drawing test on tool surfaces reinforced by hard particles

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Abstract

Deep drawing high alloy steels often causes wear issues. It is assumed that in a deep drawing process without lubrication this effect will be increased. To realize Dry Metal Forming, new tool surfaces are necessary to avoid wear. An approach is to use laser generated metal matrix composite (MMC) materials for tool surfaces. The surface is reinforced by hard particles to increase the wear resistance of the deep drawing tool. In this work the results of strip drawing test with and without lubrication of different tool surfaces are presented. In the case of lubricated strip drawing test, the friction coefficient did not differ if the tool surface is reinforced with hard particles or not. However, in a dry strip drawing test the friction coefficient is increased in the case of the MMC tool and applying normal pressure higher than 2.5 MPa. On the other hand, a significant increase of the wear resistance of the reinforced surface was observed within a dry ball-on-plate test.

Keywords: coatings, metal matrix composite (MMC), laser melt injection, Dry Metal Forming

1 Introduction

Nowadays lubrication is necessary in the vast majority of metal forming processes. To improve this production technique regarding the reduction of process steps and environmental impacts as well as avoiding health burden, research and technological development activities are required with the aim of avoiding lubricants in metal forming [1]. Therefore, approaches are presented by using liquid carbon dioxide in a deep drawing process [2] or designing the micro structure of the tool surface for a dry rotary swaging process [3]. During forming without lubrication the topography of the tool surface had a significant influence on the friction coefficient [4]. The behaviour of tailored tool surfaces for dry metal forming can be investigated by a strip drawing test [5] or using a ball-on-plate test [6].

A frequently used material in the industry is the high alloy steel 1.4301. However, forming of this steel causes adhesive and abrasive wear of the forming tool. On the one hand this leads to impairment of the surface quality of the parts formed and on the other hand the tool life is low thus the production costs increase. To counteract this problem, approaches were presented regarding the variation of the drawing radius, the lubrication and the tool material [7]. A proven tool material to form high alloy steel is aluminum bronze [8]. Results were presented to form circular cups out of 1.4301 without lubrication by using aluminum bronze as a tool material. However, wear issues appeared. So, the tool is not applicable for industrial mass production [9]. So, it was concluded that the aluminum bronze tool surface is to be reinforced to avoid wear. A possibility to reinforce the surface is to modify by laser melt injection. Thereby, a metal matrix composite (MMC) would be produced. In lubricated forming processes laser generated MMC tool surfaces potentially decreased the friction coefficient and the wear [10].

In this work investigations about the tribological behavior of laser generated MMC surfaces for dry metal forming is presented.

2 Experimental details

2.1 Laser generated MMC surface

For laser melt injection a Trumpf HL4006D Nd:YAG laser was used. The laser power was 400 W and the laser spot diameter was 1.2 mm. A process speed of 225 mm/min was used. The powder supply was coaxial by using Precitec YC50 laser processing head. The hard particles were fed into the process zone by using the pneumatic powder feeder GTV MF-PF-2/2. The feeding gas was Argon and the flow rate of the gas was 7.5 l/min. The powder feed rate amounted to 8 g/min. Furthermore, Argon acted as shielding gas in

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the center with 16 l/min as well as coaxial with 8 l/min. Spherical fused tungsten carbide (SFTC) particles from the company Oerlikon Metco were deployed. The particle grain size was in a range from 45 µm to 106 µm. Figure 1 shows scanning electron microscopy (SEM) images of the hard particles.

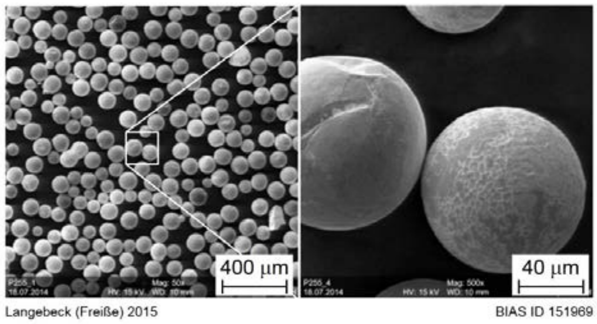


Fig. 1: Scanning microscopy (SEM) images of the hard particles

Aluminum bronze with a chemical composition of CuAl10Ni5Fe4 acted as substrate material. The dimensions of the substrates were 10 x 25 x 36 mm³. Before and after the laser melt injection process the substrates were weighted to calculated the powder catchment efficiency. The laser generated MMC surface was post process laser remelted by using the same process parameters without injecting hard particles. The surfaces were ground manually by using a plate grinding machine and grinding discs with FEPA P80 and FEPA P200 in each case for ten minutes.

Furthermore, laser ablation was applied to selectively reset the matrix of the composite material. Consequently, the hard particles stood out of the surface and a supporting plateau out of hard particles was formed. For laser ablation the picosecond laser Trumpf Micro5050 was applied. The Xiton Harmonic Box (XHB) was applied to convert the fundamental wavelength of 1030 nm to the wavelength of 515 nm. The spot diameter amounted to 50 µm and the fluence amounted to 0.77 J/cm². The scanner hurrySCAN®II was used to control the movement of the laser beam in x- and y-directions. For positioning the substrate in z-direction the linear thrust unit ISEL LES 5 was used. The positional accuracy was ± 0.02 mm. The scanning speed was 2 m/s and the repetition rate was 200 kHz. Hence the overlapping degree of the laser ablated points in the feed direction was 80 %. The overlapping degree of the tracks was also adjusted to 80 %. No shielding gas was applied.

For imaging and measuring of the laser modified surfaces the digital 3D light microscope Keyence VHX-1000 was used by applying a magnification of 1000. An average of the distance between the top of the hard particles and the matrix was measured (in the following: "peak-to-valley height").

2.2 Tribological testing

The testing of the tribological behaviour of the tailored surfaces was investigated by using a strip drawing test and an oscillating ball-on-plate test. The strip drawing test was carried out with and without lubrication. Wisura ZO3368 was chosen as lubricant. On the one hand the tribological behaviour of the MMC and on the other hand the tribological behaviour for reference of aluminum bronze CuAl10Ni5Fe4 and cold worked steel 1.2379 was investigated. The strip drawing speed was varied between 2 mm/s and 10 mm/s. Three different contact pressures were applied: 2.5 MPa, 5 MPa and 7.5 MPa. The sheet material was high alloy steel 1.4301 and the sheet thickness amounted to 0.5 mm. The dimension of the strips was 100 x 15 mm². The drawing length amounted to 70 mm. The normal load was applied by a micrometer screw and measured by a piezo sensor from the company Kistler with a measuring range of ± 500 N. The strip drawing apparatus was installed in a Zwick Roell Z250 tension testing machine. The drawing force was measured using a 5 kN sensor. For calculating an average of the friction coefficient, the drawing force in a range of the drawing length between 20 mm and 50 mm was considered.

The ball-on-plate test had an oscillating motion cycle. The tribometer CETR UMT-3MT was deployed. The counter body was a rod and the end was shaped as spherical calotte with a diameter of 10 mm. It was made of high alloy steel 1.4301 and the hardness amounted to 242 HV0.5. The normal load was 10 N. The test was carried out in a temperature regulated climate chamber to perform the test in constant environmental conditions. The humidity during the test was 40 % ± 1 % and the temperature was 24 °C ± 1 °C. The wear path was 10 mm and the sliding speed amounted to 10 mm/s. The sliding distance was 864 m. In the oscillating test, a sinusoidal speed profile was given. To evaluate the results for the linear movement between the turning points, the average of the friction coefficient was calculated through the software MatLab. The weight loss of the specimens was measured using a balance with a resolution within ± 0.1 mg to determine the wear.

3 Results

3.1 Laser generated MMC surface

By means of a small spot diameter and a large degree of overlapping smooth surfaces could be realized whereby the surface waviness was low. Through grinding the MMC surface, a peak-to-valley height of 2 µm was observed. Furthermore, the copper alloy matrix of the MMC could successfully be ablated. Figure 2 is showing a top view picture of the laser generated and laser ablated surface. Through the amount of repetitions of the laser ablation process the matrix could be laser ablated successively. So the peak-to-valley height was 6 µm by applying 70 repetitions and 12 µm by applying 160 repetitions.

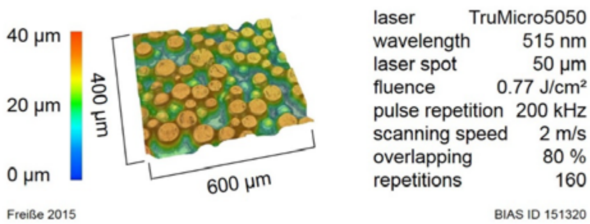


Fig. 2: Top view of the ablated metal matrix composite

3.2 Strip drawing test

Figure 3 exemplarily shows the transient measurement data during the strip drawing test for each surface with and without lubrication by applying 2.5 MPa surface pressure and a strip drawing speed of 10 mm/s. In the lubricated strip drawing the required force of all specimens was lower compared to the dry strip drawing test. It is shown that the required force was constant in the case of the MMC surface. In contrast, applying bronze and steel as tool material and using lubrication a decreasing force was observed. In particular, using bronze and steel surfaces in a dry strip drawing caused peaks in the force-path curves. In the case of the MMC surface without lubrication a smooth force-path curve was achieved.

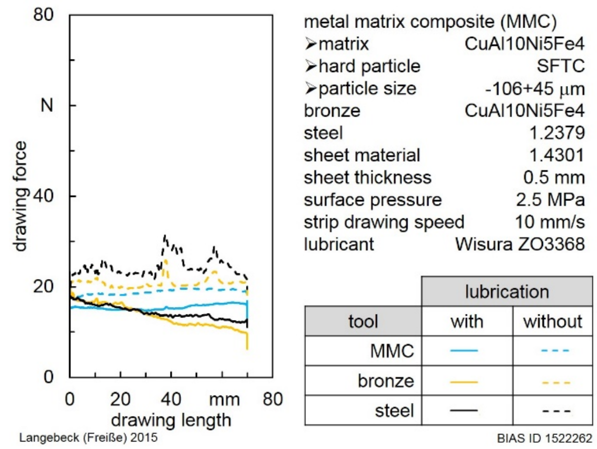


Fig. 3: Transient measurement data during strip drawing test at a surface pressure of 2.5 MPa

By applying a surface pressure of 5 MPa (Figure 4) the same effects occurred regarding the force-path curve as compared to the results by using a surface pressure of 2.5 MPa as shown in Figure 3. The drawing forces were approximately doubled. An increased force within the drawing path was measured in the case of the MMC surface in a dry strip drawing test..

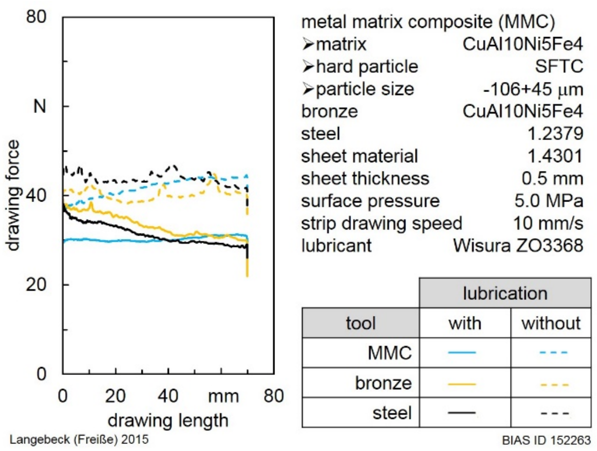


Fig. 4: Transient measurement data during strip drawing test at a surface pressure of 5 MPa

In Figure 5 the transient measurement data of the force-path curve during the strip drawing test by applying a surface pressure of 7.5 MPa is given. The drawing forces were approximately tripled compared to the forces at surface pressure of 2.5 MPa. The same qualitative course of the path-force curves were measured compared to the results of a surface pressure of 5 MPa.

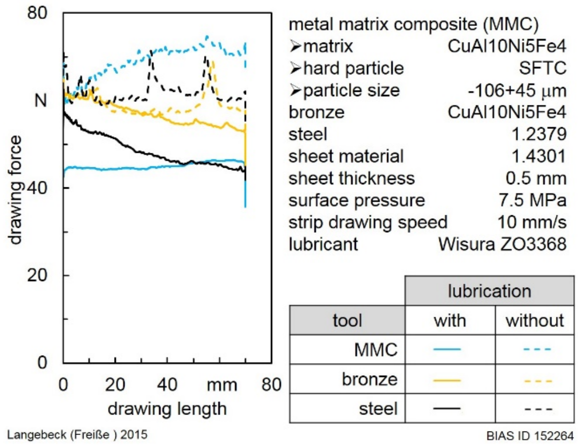


Fig. 5: Transient measurement data during strip drawing test at a surface pressure of 7.5 MPa

Figure 6 is showing the influence of different process parameters in a strip drawing test on the friction coefficient by applying a surface pressure of 2.5 MPa. The friction coefficient of the lubricated sliding amounted from 0.09 to 0.12 and of the dry sliding from 0.12 to 0.16. No significant influence of the sliding speed or of the tool material on the friction coefficient was observed. The standard deviation of the friction coefficient of all results were in a range between 0.0004 and 0.0139.

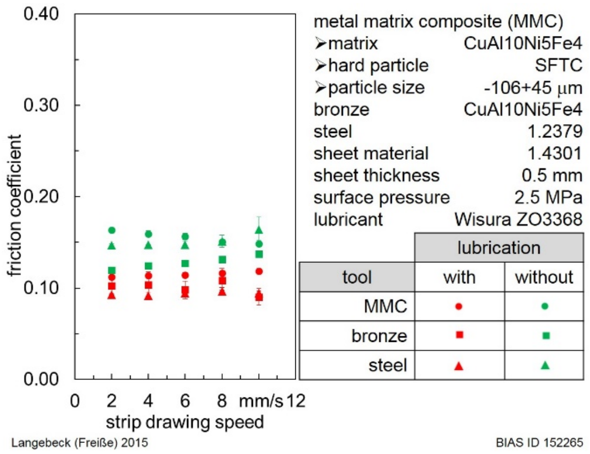


Fig. 6: Results of the strip drawing test at a surface pressure of 2.5 MPa

The friction coefficient in dependence of the surface material, the lubrication and the drawing speed by applying a surface pressure of 5 MPa are shown in Figure 7. In the case of lubricated sliding, the friction coefficient were lower compared to the the dry sliding process. There also was no significant influence of the sliding speed. Particular, the friction coefficient in dry sliding and applying the MMC surface were higher. The standard deviation of all results of the friction coefficient were in a range between 0.0004 and 0.007.

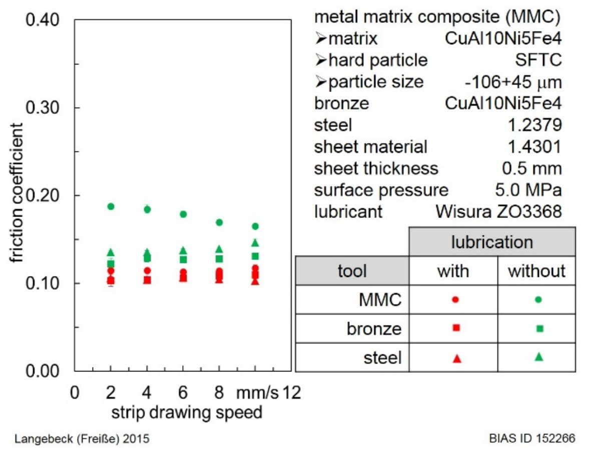


Fig. 7: Results of the strip drawing test at a surface pressure of 5 MPa

Applying a surface pressure of 7.5 MPa resulted in a significant increase of the friction coefficient in the case of the non-lubricated MMC surface (Figure 8). Indeed, in case of lubricated strip drawing the MMC surface showed no difference in the tribological behaviour compared to the results of steel and bronze. Except of the dry strip drawing with the MMC surface, no significant influence of the sliding speed on the friction coefficient was observed. The standard deviation of all results of the friction coefficient amounted from 0.007 to 0.0081.

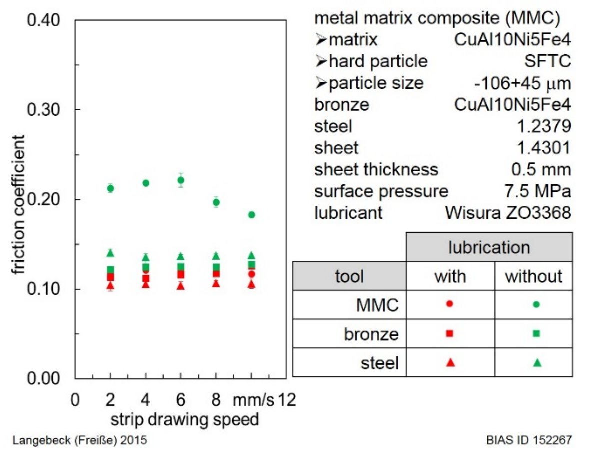


Fig. 8: Results of the strip drawing test at a surface pressure of 7.5 MPa

The influence of the peak-to-valley height on the friction coefficient in a dry strip drawing test is illustrated in Figure 9. By using the ground MMC surface and applying 2.5 MPa surface pressure as well as at a strip drawing speed of 10 mm/s a friction coefficient of 0.14 was measured. When the peak-to-valley height was increased by laser ablation, a higher friction coefficient was measured. The friction coefficient amounted to 0.22 when the peak-to-valley height was 6 µm and the friction coefficient was 0.29 in the case of a peak-to-valley height of 12 µm.

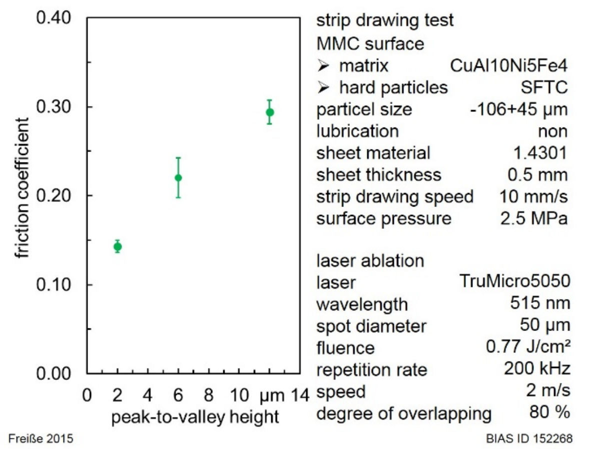


Fig. 9: Influence of the peak-to-valley height on the friction coefficient in a dry strip drawing test

3.3 Ball-on-plate test

Figure 10 is illustrating the results of the dry oscillating ball-on-plate test. The investigations revealed that the cold worked steel showed the highest friction coefficient of 0.81. The friction coefficient of the MMC surface was 0.56 and the friction coefficient of the bronze surface amounted to 0.38. It is assumed that the higher friction coefficient of the MMC surface was caused by the hard particles of this composite material. The primary wear of the MMC surface was on the bronze matrix because of the lower hardness. So the hard particles remained and stood out of the surface. They acted as a mechanical hindrance to the movement of the counter body. Regarding the wear, it can be seen that using the MMC surface resulted in the lowest weight loss of 5.4 mg. In contrast, the bronze substrate had a wear of 22.7 mg. The MMC surface showed less wear because of the reinforcement with hard particles. The wear of the steel amounted to 16.4 mg. The standard deviation of the friction coefficient were in a range from 0.014 to 0.036 and the standard deviation of the weight loss amounted from 1.16 mg to 2.48 mg.

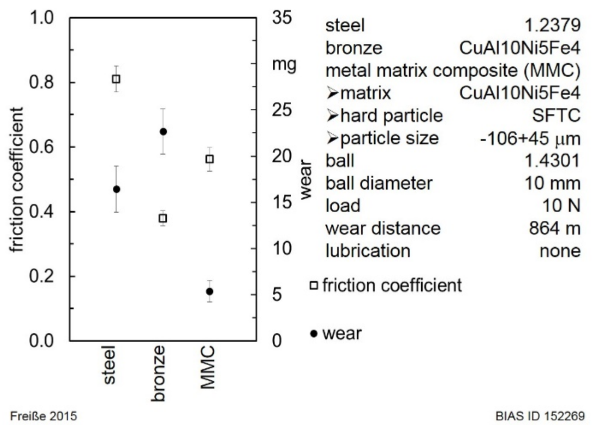
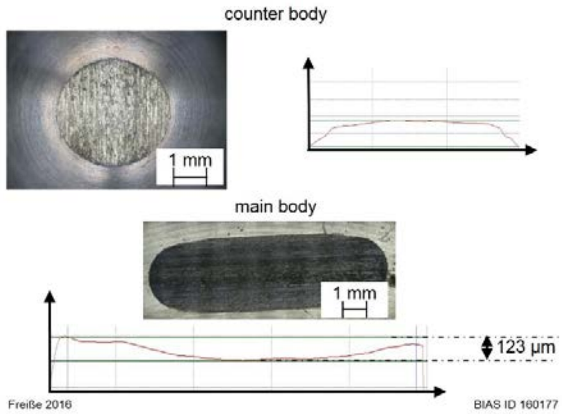


Fig. 10: Results of the dry oscillating ball-on-plate test

Steel as main body in the ball-on-plate test resulted in a flattened counter body. Figure 11a is showing images and profiles of the surfaces produced by a digital microscope. Detail images taken with a Scanning Electron Microscope (SEM) are given in Figure 11b. Scratches became visible both on the counter body and main body. The structure of the rugged surfaces indicates the influence of adhesive wear during the ball-on-plate test. It could not be clearly evaluated in how far abrasive wear occurred.



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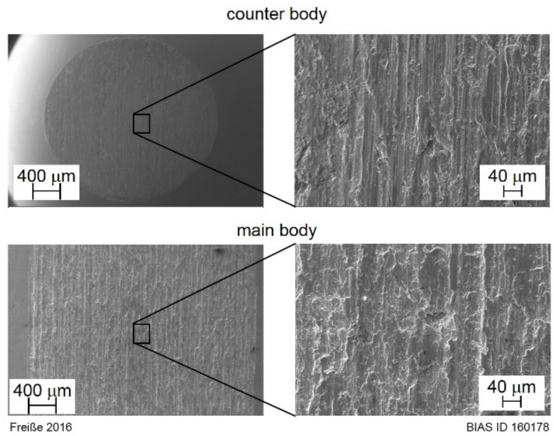
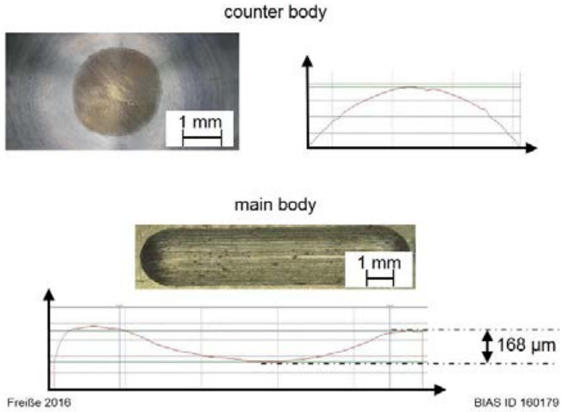


b)

Fig. 11: a) Digital microscope pictures and b) SEM pictures of the counter body and main body made of steel

In the case of the bronze main body the counter body was not flattened and the spherical form of the counter body remained. Bronze colour was visible on the counter body (Figure 12a). It is assumed that material of the main body was transferred to the counter body caused by adhesive wear. The depth of the wear volume in the main body was deeper in contrast to the depth of the wear volume when steel acted as main body. This is roughly correlating with the weight losses shown in Figure 10. In Figure 12b SEM pictures of the counter body and main body made of bronze are shown. Contrary to the wear effects in the case of the steel main body the damage did not lead to scratches on the surfaces. Here, scuffing effects can be identified which is a clear indication for adhesive wear.



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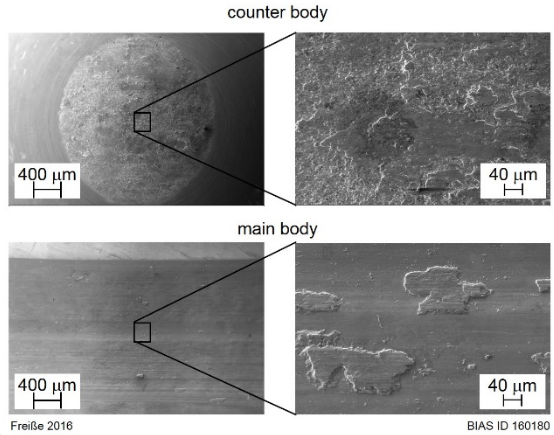
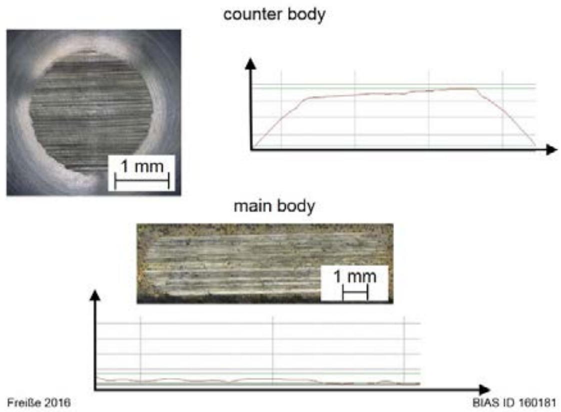


b)

Fig. 12: a) Digital microscope pictures and b) SEM pictures of the counter body and main body made of bronze

Figure 13a is showing the digital microscope pictures of the surfaces in the case of the MMC main body. The counter body was flattened compared to the result when bronze acted as main body. That means that the reinforcement of the bronze main body by hard particles caused a significant change in the wear behaviour of the counter body. However, there was no significant depth of the wear volume in the main body out of MMC. Both on the counter body and on the main body scratches are visible. Within the detailed images produced by SEM (Figure 13b) it becomes apparent that a combination of adhesive and abrasive wear occurred. On the one hand the counter body rather showed abrasive wear in form of scratches. On the other hand the main body exhibited break out areas which is a result of adhesive wear.



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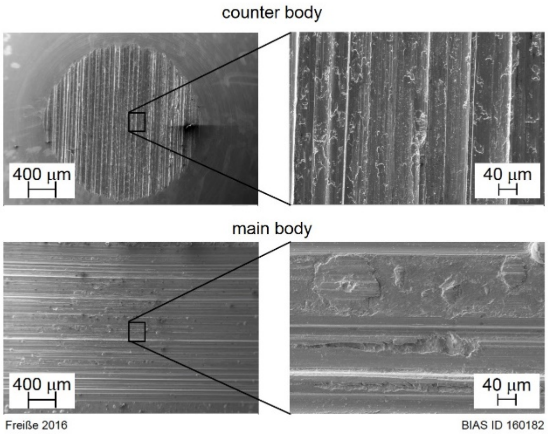

b)

Fig. 11: a) Digital microscope pictures and b) SEM pictures of the counter body and main body made of MMC

4 Discussion

Regarding the friction law the friction coefficient would be always less than 0.577 for von-Mises yield criterion or 0.5 for Tresca yield criterion. For practical applications the friction coefficient should be lower than 0.2 [11]. The results of this work revealed that the MMC surface meets the requirements in dry strip drawing test under the conditions of a surface pressure lower than 5 MPa and a peak-to-valley height lower than 6 µm. This appears to be valid at least for the test conditions which simulate low volume production. Furthermore, a high wear resistance of the tool surface is required. In a dry oscillating ball-on-plate test the increased wear resistance of the reinforced surface could be verified.

The MMC surface showed the same tribological behaviour in the lubricated strip drawing test compared to bronze and steel tools by applying different surface pressures and sliding speeds. Furthermore, this result was also found in dry sliding at a surface pressure of 2.5 MPa. However, by applying a surface pressure higher than 2.5 MPa the friction coefficient were shifted to higher values. This effect could be due to the Hertzian pressure caused by the spherical hard particles. This effect could be clarified by setting back the matrix by laser ablation: By increasing the peak-to-valley height the friction coefficient increased significantly. This is traced back to the decreasing supporting effect of the matrix.

5 Conclusion

It can be shown that the strip drawing test is an applicable test methods to examine the friction coefficient for dry and lubricated sliding. On the other hand the oscillating ball-on-plate test is a practicable procedure to investigate the wear resistance of tool surfaces. By reinforcing aluminum bronze with spherical tungsten carbide the weight loss could be decreased significantly by 76 %. However, within the dry strip drawing test the friction coefficient increased in the case of the MMC surface at surface pressures higher than 2.5 MPa and by increasing the peak-to-valley height. It can be concluded that the supporting effect of the matrix and the surface pressure had a significant influence on the friction coefficient in the non-lubricated strip drawing test in the case of MMC surface.

Acknowledgements

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