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Characterization of the tribological behaviour of tool surfaces depending on higher contact pressures

Freiße, H.*[1], Schmidt, S.[1], Seefeld, T.[1]

[1]BIAS – Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Straße 5, D-28359 Bremen, Germany

Abstract

During deep drawing, different contact pressures between the sheet and the tool surface occur. Under the blankholder the contact pressure is relatively low, can be analytically calculated and adjusted. Generally, the highest contact pressures result at the drawing radius, which can be calculated using finite element methods. Besides of the material combination of the tool and the sheet, the surface structures, the intermediate medium and the relative speed, the contact pressures have a significant influence on the tribological system. Strip drawing tests offer the possibility to characterize tribological systems for sheet metal forming under variation of the contact pressure.

In this work, the tribological behaviour of three different tool surfaces was investigated: hot-working steel, aluminium bronze and metal matrix composite (MMC). The MMC-surface had a supporting plateau out of hard particles with a depression of 3 µm. The tests were carried out with and without lubrication by applying different contact pressures up to 20 MPa. Using hot-working steel in dry-sliding resulted in friction coefficients at times higher than 1 even at low surface pressures of 4 MPa. It was shown that the friction force was successively increased each time of strip drawing. This was an indication for significant progressive wear in dry sliding, whereby the first strip draw led to a smooth force-path curve comparable to lubricated sliding and the subsequent experiments showed pronounced peaks in the force-path curves. By contrast to the tribological behavior of the hot-working steel, the friction coefficients in dry sliding using aluminium bronze and the MMC surface were significantly lower. By increasing the surface pressure by a factor of five the friction coefficients in lubricated strip drawing were decreased by up to 8% and in dry sliding the friction coefficients were increased by up to 63%.

Keywords: strip drawing test, metal matrix composite (MMC), hot-working steel, aluminium bronze, contact pressure, Dry Metal Forming

1 Introduction

Metal forming plays in important role in the industrial mass production [Jes08]. New research work (e.g. Dry Metal Forming) is focused on the optimization of the production technology in economic and ecological aspects in the future [Vol14] and current practical developments (e.g. lightweight construction) offer the possibility to realize new even more competitive products [Lie17].

For analyzing the process of metal forming two thematic categories can be defined: stress conditions in the sheet material during forming which can lead to cracks or wrinkle formation and the interaction between the workpiece and the tool which is the main subject of investigations in the scientific field of tribology.

For analyzing complex tribological systems in metal forming, the systems are modelled by simple test methods. Tribology testing aims on the one hand the quantification of friction and on the other hand the determination of the wear behavior. In generally, the main influence factors which are focused on in different scientific investigations are e.g. the material combination [Sch14], the intermediate [Woe17], the surface macro and micro structures [Sor99], the temperature [Neu06], the contact pressure [Cai09], the sliding speed [Bas07] or the duration of the testing [Wu04].

Regarding the selection of the testing method an essential distinction must be made between open and closed tribological systems. In closed tribological systems the two materials are repeatedly in contact [Czi74], e.g. in a reciprocating pin-on-disc test [Mak17] or in an oscillating ball-on-plate test [Son17]. Thereby the formation of the third body can occur which have a significant influence of the tribological behavior [Sto13]. Depending of the geometry of the counter bogy (e.g. ball) Hertzian stress occur and contact pressures up to

*E-mail address of corresponding author: freisse@bias.de

1100 MPa result even at low normal loads of 15 N [Fre16]. A closed tribological system with an oscillating motion can be applied e.g. to analyze the effects between the piston and the cylinder in a combustion engine and tests with a movement only in one direction (e.g. pin-on-disc test) are used to investigate the tribological system e.g. in bearings. However, for sheet metal forming open tribological test methods should be applied e.g. strip drawing tests. Generally, the wear is indirectly measured in form of the surface deformation in the case of testing a few strokes. There are strip drawing apparatus that enable automatically testing by applying up to ten thousand of strokes. Using a tool geometry for cylinder-plane test contact pressure up to 575 MPa can be adjusted. There is the possibility to determine the wear directly in form of mass loss [Gro11].

2 Experimental details

The experimental details for producing the strip drawing jaws, for performing the tribological testing in a strip drawing test and for analyzing the change of the surface structure are described in [Fre17a].

In this work, MMC tool surfaces are applied with a depression of 3 µm. In addition, the tribological behavior of two conventional tool surfaces were investigated: aluminium bronze CuAl10Ni5Fe4 and hot-working steel 1.2379 (Fig. 1).

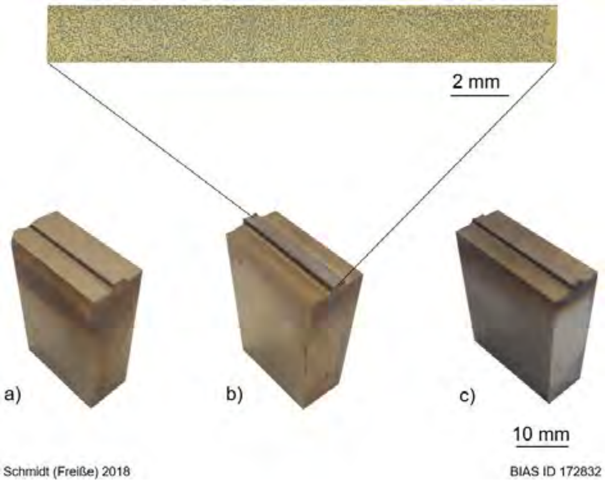

Figure 1: Strip drawing jaw after electrical discharge machining (wire-cut). a) out of aluminium bronze b) out of aluminium bronze reinforced with hard particles, c) out of hot-working steel

In strip drawing the dry sliding strokes (1. stroke, 2. stroke, 3. stroke, ….) were carried out at first. After the dry sliding tests, the lubricated tests were performed with the same tool. The tools were not removed from the strip drawing apparatus. For every tool material (hot-working steel, aluminium bronze, MMC) one tool set was used. One tool set consists of two drawing jaws. For every stroke, a new sheet was applied. This represents an open tribological system.

3 Results

3.1 Hot-working steel tool

Fig. 2 is showing the drawing force in the case of using tool steel depending on the drawing path for the first strip drawing stroke and for the fifth drawing stroke in dry sliding by applying a contact pressure of 4 MPa. For every stroke, a new sheet material was applied. It can be seen, that within the first strip drawing a smooth curve was measured. In contrast, after five strip drawing strokes the drawing force was increased significantly and the force-path curve showed pronounced peaks. These peaks reflect an intensive interaction between the sheet and the tool surface and potentially indicate a stick-slip effect [Pes03]. A stick-slip effect indicates the occurrence of adhesive wear [Gro11]. The drawing forces within the evaluation range were used to calculate the averages of the drawing forces of every stroke (Fig. 3).

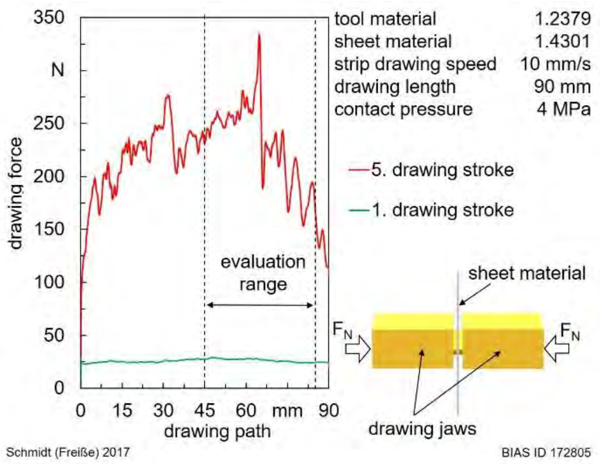

Figure 2: Dry strip-drawing force depending on the strip path using a tool surface out of hot-working steel in dry sliding and applying a contact pressure of 4 MPa

In Fig. 3 it can be seen, that the strip drawing forces were progressively increased by every stroke in dry sliding until the fifth stroke.

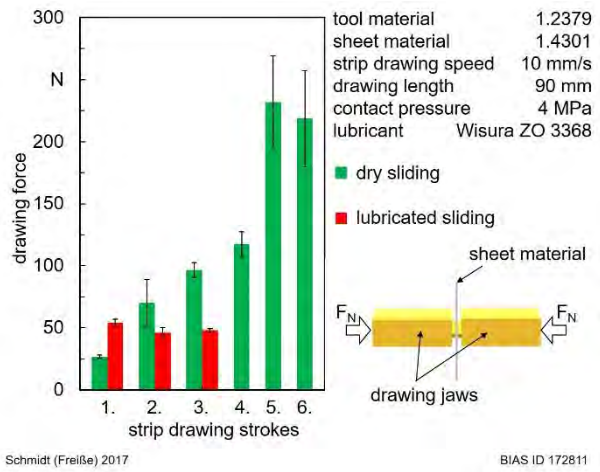

Figure 3: Strip-drawing forces for every single stroke using a tool surface out of hot-working steel by applying a contact pressure of 4 MPa

The forces were increased within in the first three strokes by 369% and within the first five strokes by

872%. The sixth stroke showed essentially the same force as the fifth stroke. The increasing forces can be traced back to surface deformation of the tool surface. The deformed tool surface after dry sliding influenced the following experiments in lubricated sliding. So, the first stroke in lubricated sliding showed a higher force compared to the first strip drawing stroke in dry sliding.

However, the friction coefficients calculated from the first three strokes in dry sling were higher compared to lubricated sliding as expected (Fig. 4). The friction coefficient in lubricated sliding amounted to 0.28 and in dry sliding to 0.37. In contrast, the mean friction coefficient investigated from the third to the sixth stroke was 1.

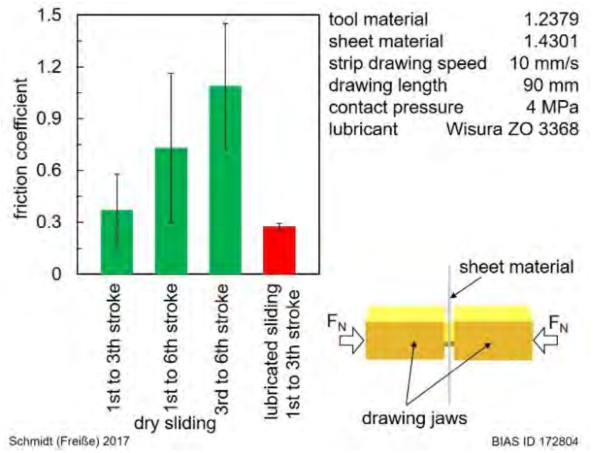

Figure 4: Friction coefficients of the hot-working steel 1.2379 by applying a contact pressure of 4 MPa

The surface roughness Sa of the sheets before testing was 0.35 µm. The surface roughness of the sheets was just slightly increased within the first stroke in dry sliding (Fig. 5). A significant deformation of the sheet surface was measured after six dry sliding strokes. This is correlating to the increased drawing forces (Fig. 3). It is assumed that an intensive damage of the tool surface occurred after six dry strokes. Adhesive wear could result in form of adhered sheet material on the tool surface. These partially adhered sheet materials on the tool could lead then again to grooves in the surface of the sheets even in the following lubricated sliding experiments at it can be seen in Fig. 6.

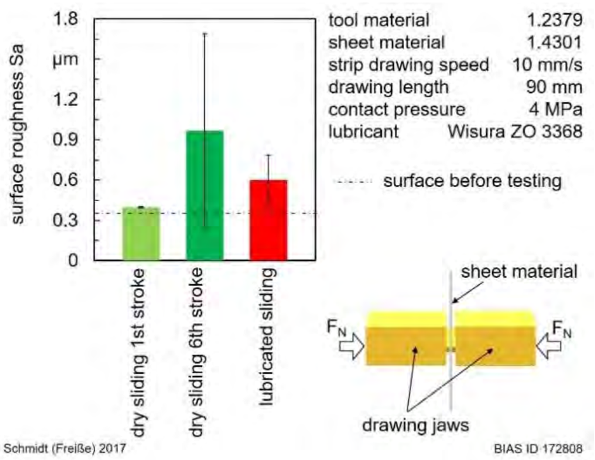

Figure 5: Surface deformation of the sheets in the case of using hot-working steel 1.2379 and contact pressure of 4 MPa

The depth of the groove is about 8 µm. The sheet surface was plastically deformed. The area deformed (1) amounted to 603 µm² and the area of the groove (2) amounted to 840 µm². So, it is assumed that mass loss occurred in form of abrasive and/or adhesive wear.

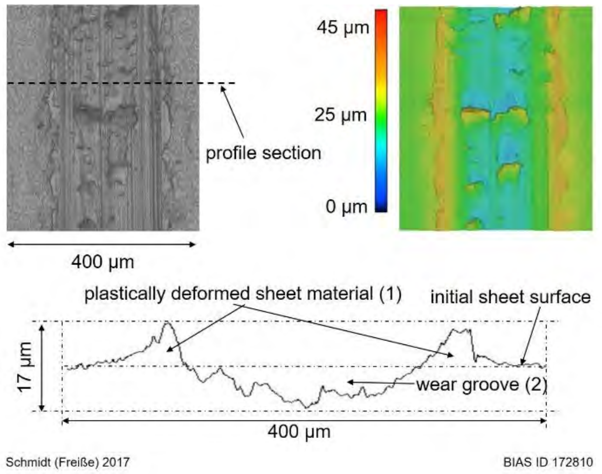

Figure 6: Microscope image of a groove in the sheet surface after lubricated sliding using hot-workingsteel

3.2 Aluminium bronze tool

In Fig. 7 the drawing forces are figured out in the case of using aluminium bronze tool and contact pressures of 4 MPa and 20 MPa. The forces were higher in the case of dry sliding compared to the forces in lubricated sliding. Furthermore, the forces were increased by applying higher contact pressure. Particularly the drawing forces were successively increased within the first three strokes by up to 45% in dry sliding at high surface pressure. However, this is not an indication of significant deformation of the tool surface as it occurred in using hot-working tool steel because there was no pronounced change in the surface roughness (Fig. 8).

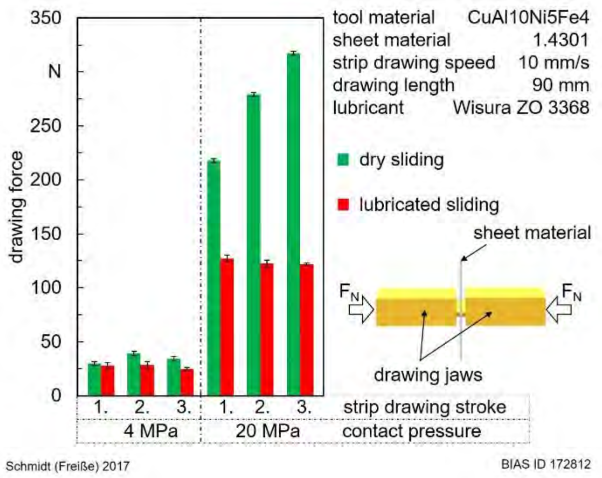

Figure 7: Strip-drawing forces for every single stroke using a tool surface out of aluminium bronze

The change of the surface roughness of the sheets depending on the contact pressure is depicted in Fig. 8. There was no significant influence of the contact pressure on the surface deformation.

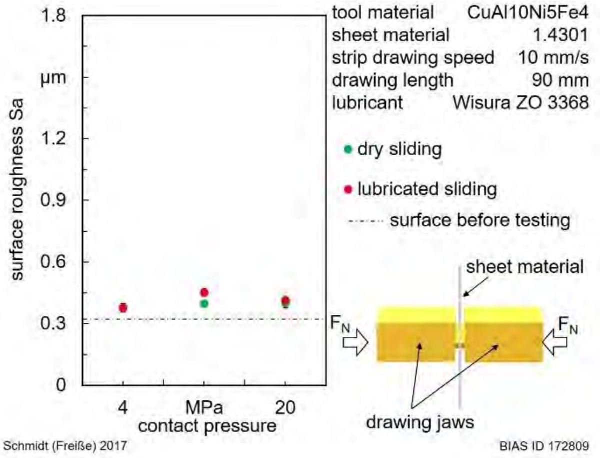

Figure 8: Deterioration of the sheet surfaces depending on the contact pressure by applying aluminium bronze tool in dry and lubricated sliding

The friction coefficients in dry sliding were higher compared to the friction coefficients in lubricated sliding (Fig. 9). In the case of lower contact pressure there is just a small difference in the friction coefficient of dry and lubricated sliding. Using high contact pressure led to a significant increase of the friction coefficients in dry sliding. The friction coefficients were increased up to 58% when the contact pressure was in increased from 4 MPa to 20 MPa.

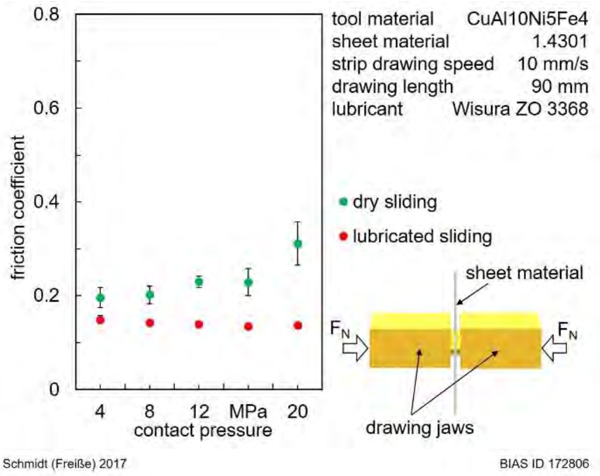

Figure 9: Friction coefficients depending on the contact pressure using a tool surface out of aluminium bronze

3.3 MMC tool

The averages of the drawing forces in the case of using MMC tool surface are shown in Fig. 10. The drawing forces in dry sliding were higher compared to the drawing forces in lubricated sliding. By applying higher contact pressures, the drawing forces varied stronger in dry sliding. There was no strong progressively increase of drawing forces observed like it was occurred in the case of using hot-workingsteel and aluminium bronze as tool materials. So, it is assumed that there is no wear of the tool surface.

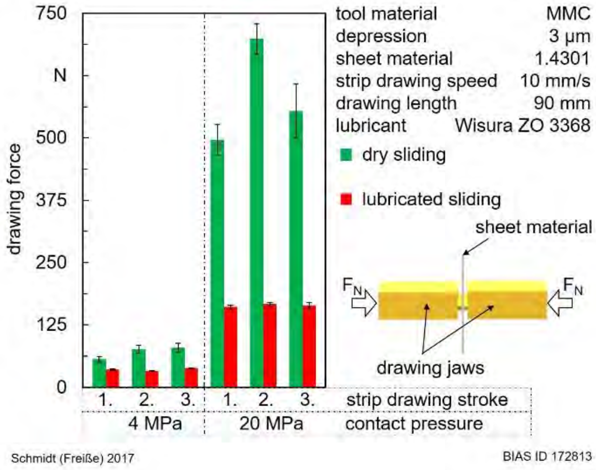

Figure 10: Drawing force depending on the contact pressure by applying MMC tool in dry and lubricated sliding

The friction coefficients depending on the contact pressure in the case of using MMC tool surface are shown in Fig. 11. The friction coefficients in dry sliding were higher as in lubricated sliding. By increasing the contact pressure from 4 MPa to 20 MPa a slight decrease of the friction coefficients in lubricated sliding was observed and an increase of the friction coefficients in dry sliding up to 63% was determined.

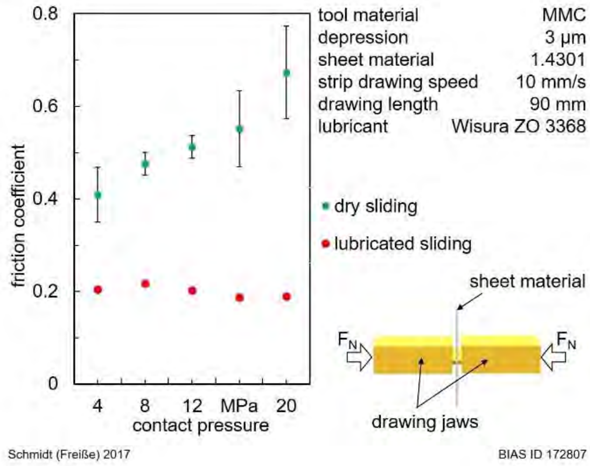

Figure 11: Friction coefficients using a tool surface out of MMC depending on the contact pressure in dry and lubricated sliding

By increasing the contact pressure from 4 MPa to 12 MPa the surface roughness is rapidly increasing (Fig. 12). This could be caused by the penetration of the hard particles into the sheet surface. However, there is no further difference in the surface roughness when higher contact pressure about 20 MPa was applied. The MMC surface had a depression of 3 µm. The depression is the distance between the supporting plateau out of hard particles to the rejected matrix. It is assumed that in the case of 12 MPa the particles penetrated about 3 µm into the sheet material. So, by applying higher contact pressure the particles could not deeper penetrate in the sheet material and in consequence the surface roughness of the sheets was not increased.

In lubricated sliding the surface roughness was increased in the case of higher contact pressure. The surface roughness in lubricated sliding was lower compared to the surface roughness in dry sliding. It is assumed that hydrostatic pressure of the lubricant weakened the penetration of the particles.

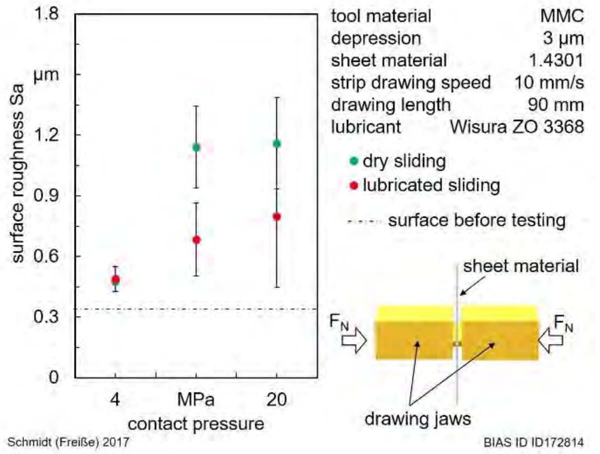

Figure 12: Deterioration of the sheet surfaces depending on the contact pressure by applying MMC tool in dry and lubricated sliding

4 Discussion

In this work, the surface pressure was incrementally increased by 4 MPa. By applying tool surfaces out of aluminium bronze and MMC there is no significant influence of the contact pressure in dry sliding on the friction coefficient in the case of marginal variation of the surface pressure (e.g. from 4 MPa to 8 MPa) under consideration of the standard deviations. This is in accordance with other results in dry strip drawing applying surface pressure of 1.5 MPa and 3 MPa [Mer15]. However, in deep drawing of high alloy steels (e.g. 1.4301) the values of surface pressure can vary in a range from 2.5 MPa under the blankholder to 200 MPa at the drawing radius. Locally high contact pressure up to 400 MPa can occur [Kuw07].

In this work, it was shown that higher contact pressure led to an increase of the friction coefficient in dry sliding up to 58% by applying aluminium bronze tool when the surface pressure was increased from 4 MPa to 20 MPa. In [Sev99] a decreasing friction coefficient in dry sliding is presented applying a strip drawing test. However, in these experiments the materials were not cleaned. It can be assumed that the results could be influenced by anticorrosive oil on the sheet and by residues of cooling lubricants on the tool used for machining. So, these results should be critically evaluated regarding the definition of Dry Metal Forming [Vol14]. An assessment of different cleaning methods to investigate the tribological behavior for Dry Metal Forming is given in [Alm17]. In this work, the sheets and the tools were cleaned by a cleaning procedure as described in [Fre17b]. Without a protecting intermediate the surfaces can be in direct contact and interatomic forces can come into effect. These processes are used in friction welding to join materials. In sheet metal forming relative low contact pressure and sliding speeds are applied compared to friction welding. However, interatomic forces can locally increase. This can be detected by the friction forces. When the interatomic forces locally exceed a threshold, micro welds in form of adhesive wear can occur. Whether the contact pressure have an influence on the friction coefficient in dry sliding depends on the material combination [Ghi11] or on the sliding speed [Asa09]. Oxid layers on the sheets or on the tools can act as a protecting intermediate and can prevent the increase of the friction coefficient or wear in dry sliding. By applying higher contact pressures these oxide layers can be damaged and an increase of the friction coefficient consequently occur [Mää01]. Increasing wear volume by applying higher contact pressure in dry sliding were presented in the case of using nitrided tool surface in [Mol97]. Furthermore, an increase of the contact pressure could lead to frictional heating during dry sliding. Higher temperatures could be the reason for higher friction coefficients [Pra04]. In this work higher contact pressures led to an increase of the friction coefficients. The local heat in the tool surface caused by friction must be conducted. The heat conductivity of aluminium bronze is 50 W/m*K [Car06], of spherical fused tungsten carbide is 29 W/m*K [Ber98] and of hot-workingsteel is 20 W/m*K [Sta17]. This is correlating to the friction coefficients in this work whereby the lowest friction coefficients were determined in the case of using aluminium bronze tool and the highest friction coefficients were determined in the case of using hot-workingsteel.

In this work, it was shown that the interatomic forces were especially high in the case of using hot-workingsteel tool in dry sliding. By applying a contact pressure of 4 MPa the friction coefficient was about 1 and the sheet surface was significantly deformed by adhesive wear. In contrast, by using aluminium bronze the friction coefficient amounted to 0.31 by applying 20 MPa and no significant change of the surface roughness was detected. The possibility of Dry Metal Forming of cups out of high alloy steel using aluminium bronze tool was presented in [Fre16]. However, by applying high contact pressure in dry sliding in a strip drawing test in this work, a progressive increase of the drawing forces was detected. This can be an indication of successive wear of the aluminium tool surface. It is assumed that in industrial application a significant wear of aluminium bronze would occur after ten thousands of strokes. In the case of using MMC tool surface higher friction coefficients were determined. This could be caused by penetration of the particles in the sheet surface. The penetrated hard particles acted as a mechanical hindrance to the relative movement. A significant change of the sheet surface roughness was determined. However, no progressively increase of the drawing forces were measured and so it is assumed that in industrial application less wear of the MMC tool surface would occur on continuous load compared to aluminium bronze tool.

In lubricated sliding a decrease of the friction coefficients of about 8% was measured by applying higher contact pressure when aluminium bronze or MMC acted as tool material. This correlates to the results of other research work of lubricated sheet metal forming e.g. in strip drawing with bending [Vol08], strip drawing without bending [Pes03] or in a block-on-disc test [Sav09].

This can be traced back on the hydrostatic pressure [Azu95]. However, it is depending on the tribological system whether the friction coefficient is decreasing or increasing [Kim12].

5 Conclusion

By the experimental investigations in a strip drawing test it can be concluded that hot-workingsteel is not applicable for dry sheet metal forming of high alloy steel. In the case of using aluminium bronze and MMC tool surface, the friction coefficients are higher in dry sliding compared to lubricated sliding and increase of the friction coefficient up to 63% was investigated by applying higher contact pressure because of the missing protecting intermediate.

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