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Numerical Analysis of the Tribological Mode of Action in Cold Forming of Sinus Waved Surfaces Structures

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Abstract

Cold forming processes combine high material utilization with high energy and resource efficiency. Therefore they are of great importance in production engineering. Due to high loads and stresses, liquid and solid lubricants are used to successfully perform cold forming processes. Recent findings revealed the ecological, economic, and legislative questionableness of these lubricants. The absence of lubricants would be a significant contribution to waste reduction in manufacturing processes and to the goal of the lubricant-free factory. The absence would lead to higher tribological loads which need to be compensated by either the tool or the workpiece. In this contribution a novel approach in structuring of workpieces by sinus curves as approximation of shot peened surface structures. It contains sinus curves for a determined surface structure. These sinus curves are varied in amplitude and wavelength factor. Hereby, an deterministic modeled surface structure is researched regarding contact area during surface smoothing, contact stresses, and friction force. In future work the results will enable further research on the ideal surface structure for dry metal forming.

Keywords: Dry metal forming, synthetic surfaces, Coating, (Cr,Al)N, Surface structures,

1 Introduction

High material utilization and the associated energy and resource efficiency are characteristics of cold forming processes in production engineering. Therefore, cold forged parts are typically used within the power train technology, e.g. as driving shafts. Due to the necessary high forces and continuously growing accuracy, friction occurs in the process [1, 2]. Friction needs to be reduced by liquid and solid lubricants. Lubricants are questionable because of ecological, economic, and legislative reasons. In previous researches biodegradable lubricants and/or physical vapor deposition (PVD) coatings for cold forming were surveyed. Lugscheider et al. developed a (Ti,Hf,Cr)N PVD-coating for cold metal forming applications [3]. Bobzin et al. enhanced this coating with a CrN toplayer to interact with a biodegradable lubricant for environmentally benign metal forming. Furthermore, a special tool coating with self-lubricating disulfides for dry metal forming was researched [4, 5]. New approaches aim on a completely dry metal forming process, which significantly contributes to waste reduction and to the goal of a lubricant-free factory [6, 7]. In the field of dry forming recent research mainly discuss sheet metal forming. These results reveal the possibility to adapt the knowledge for the case of dry metal forming [8, 9]. Compared to sheet metal forming, cold metal forming goes along with higher contact pressures and surface expansion of the workpiece. The tool loads in dry sheet metal forming are higher than in dry sheet metal forming. In cold metal forming these loads are increasing even more. A first schema to picture all demands and relations in dry forming is shown in Fig. 1. Firstly pre-treatment of the surface structure needs to be investigated. For PVD-coatings it is necessary to primary initially a plasma treatment [10, 11]. Without that treatment the hard coating will not be able to withstand the increased tool loads of dry metal forming. The Surface Engineering Institute (IOT) will deal with that subject. Another possibility to fulfill these demands, is to investigate surface structures on workpieces, with which will be dealt by the Laboratory for Machine

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Tools and Production Engineering (WZL) [12-16], see Fig. 1.

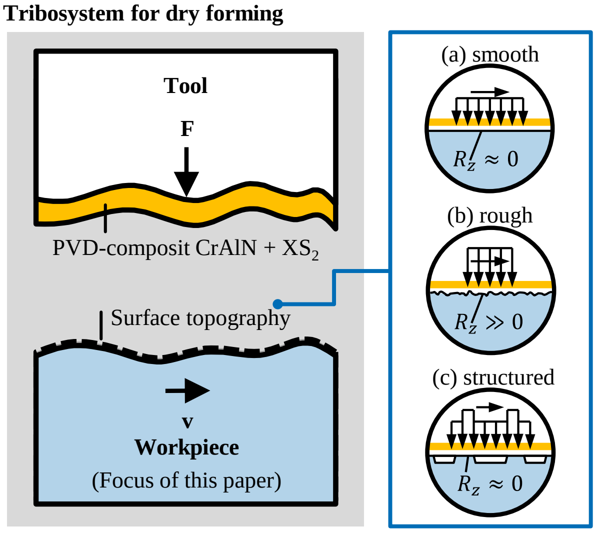

Figure 1: Illustration of the proposed dry tribological system. The IOT focusses on the (Cr,Al)N PVD-coating with self-lubricating disulfides. The WZL researches surface structures on workpieces to minimize friction and tool loads. Legend: F_N = Normal force, v = sliding velocity, Rz = surface roughness.

Secondly changes of the workpiece surface structure need to be researched. FE-models are implemented to initially investigate dry metal forming contact. The generated simulations compared to experimental results showed the tendency that dry metal forming can be successfully integrated in production processes.

The approach in this work is divided in two steps. The first step will give an overview to performed researches and results of dry metal forming. In the next step the modeling of stochastic shot peened surface structures will be reviewed regarding sinus curves. These generated surface structures are investigated regarding contact area, contact stresses and friction force. The results will lead to specified surface design to support the dry forming process.

2 Preliminary works

In Section 2 an overview of preliminary work will be given. It will contain work from the 'Surface Engineering Institute' (IOT) which focused on applying a surface coating on the tool via physical vapor deposition. Further work regarding shot peened surface structures of semi-finished parts are also reviewed. In need of an optimized production process two options will be combined. Therefore it is possible to profit of advantageous of both approaches.

In comparison to the researches of the IOT, this research by the WZL aims to analyze boundary conditions for dry metal forming respectively to the workpiece. To achieve this, several approaches were researched. Firstly different surface structures generated by shot peening were investigated. These surface structures needed to be analyzed respectively their properties for dry metal forming. A new type of tribometer was developed to fulfill that [17], see Fig. 2. Conventional tribometers have a restricted mode of action as they do not allow investigating surface smoothing effects. They use the same friction path each revolution. Due to the ongoing surface smoothing per revolution the contact conditions change continuously and prohibit investigating the influence of the surface structure. The newly developed Pin-On-Cylinder (POC) tribometer provides a new frictional path each revolution by a superposition of an axial feed with a rotational movement. The normal load is applied by a hydraulic actuator.

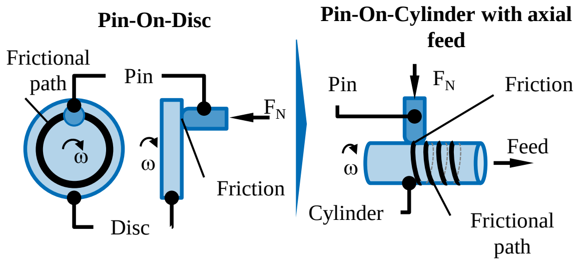

Figure 2: Illustration of the principle of the developed Pin-On-Cylinder tribometer to investigate surface structures. Legend: ω = angular velocity.

By means of this tribometer different surface structures on 16MnCr5 and 42CrMo4 were generated by shot peening. Selected structures are shown in Fig. 3 exemplarily for 16MnCr5, taken by scanning electron microscopy (SEM). The initial structure before shot peening is shown in Fig. 3(Ref). (Ce) resembles the surface after shot peening with ceramic beads. (Flat) shows flat knurled surfaces for comparison reasons. Each tribosystem was tested 30 times with the developed POC. With these results the surface roughness decreases.

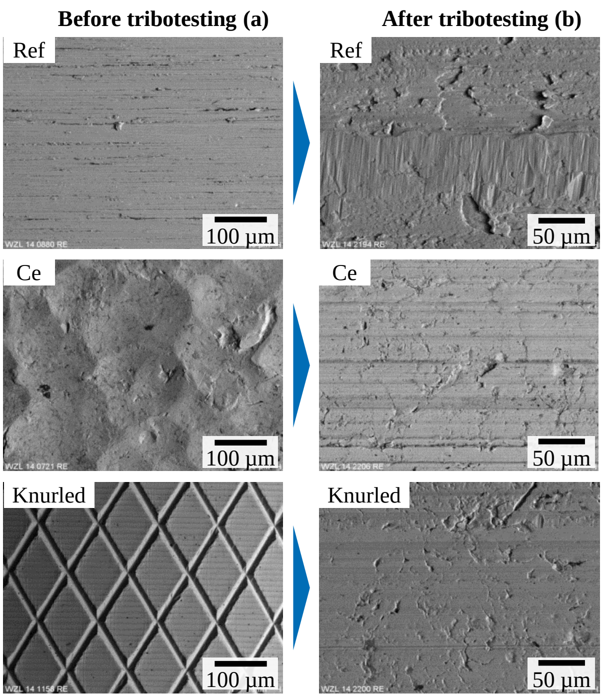

Figure 3: Image of a reference, a Ce- and a Flat-surface structure before and after tribotesting.

In Fig. 3 the surface structure after tribotesting is shown for comparison reasons. During tribotesting a normal load $F_{N,low}$ = 640 N was applied. Due to the change of appearance it is notable that the reference surface has suffered from this load. Adhesive wear is detected, whereby shot peened and knurled surface structures are less affected by wear.

In order to understand frictional and wear mechanisms in tribotesting, numerical studies were performed by WZL to globally analyze the contact stresses and locally occurring surface smoothing effects. The numerical research was divided in two different modeling approaches, see Fig 4. Firstly, a macro simulation which was used to determine the optimal path distance between to frictional paths. Additionally, stress and strain researches were carried out. In macro modeling surface structures and roughness were neglected. Secondly, a micro simulation of a cut-out model of the workpiece was carried out. Respective the true surface structure the stresses of the macro model were transferred to the micro model. The modeling was performed in Abaqus 6.13-1 using the CEL-approach. Material characteristics for the workpiece material 16MnCr5 (DIN: 1.7131, AISI: 5115) were determined in preliminary work [15].

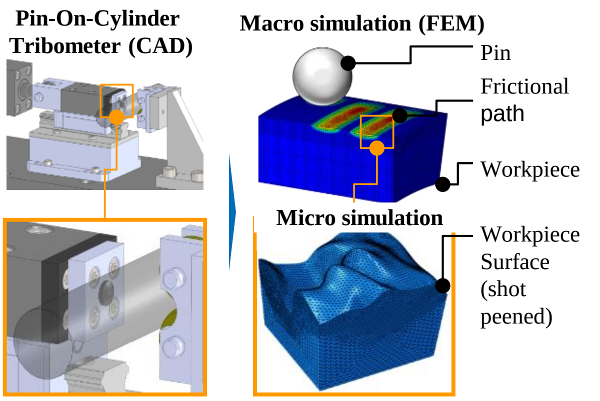

Figure 4: Modeling of the macroscopic tribometer contact and the microscopic interactions using dry and lubricated shot peened surfaces.

The micro simulation focused on surface smoothing in a dry and a lubricated forming process. The results showed that in dry forming surface smoothing will progress faster as in lubricated forming processes. This lead to lower contact stresses and therefore a lower induced friction.

The modeling required high computing times and a complex prequel measurement. Therefore, complex shot peened surfaces are approximated by deterministic sinus curves to match depth and distance of shot peened impacts.

3 Modeled surface structures by wave forms and their influence on contact area, contact pressure, and friction.

Surface structures generated by shot peening are stochastic. From a global view these structures have a definitive scheme. Therefore it is important to implement an easier approach to model that surface structure. This will lead to a better understanding of a simple smoothing process and of a future dry forming process. A new approach for surface modeling had to be found. On the one hand this approach needs to be as simple as possible to reduce computing times, on the other hand it has to map all necessary points of the surface structure. The structures were investigated regarding contact area and contact stresses. This section points out a first approach implemented by sinus curves. Firstly, the modeling will be introduced analytically. The modelling will follow to get a more detailed view on all acting parts. After that introduction results will be reviewed. Therefore the influence of the amplitude and the wavelength factor will be investigated separately on the smoothing process and growing contact area, the contact stresses, and the friction force.

The model was developed via a sinus function, where A [mm] is the amplitude, b [-] the wavelength factor, x the position and a_0 the resulting feed size of the synthesized surface, see Eq. 1:

$$a_0 = A \sin(b\pi x). \qquad (1)$$

By a varying amplitude A and wavelength factor b it is possible to generate different surface structures, Fig. 5.

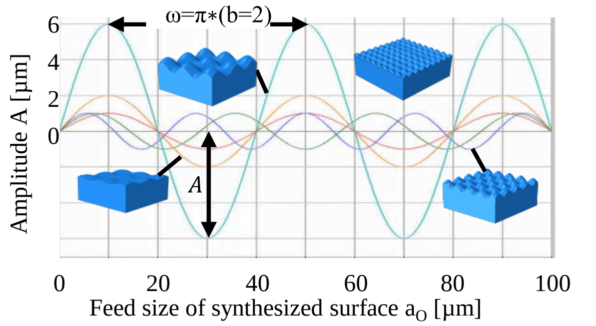

Figure 5: Changes of the surface structure by variation of amplitude A and wavelength factor b

The FE-model was set up with a punch, as smoothing tool, the workpiece with the surface structure, and with a wall, which supports the workpiece and prevents a sliding to any direction. The punch and the wall are distinguished as rigid parts, the workpiece is modeled plastically. The most important part of the workpiece is the upper one. This one is meshed with an element size of 1 µm, the transient area with 4 µm and the lower area with 8 µm, as the resolution there does not need to be as detailed as in the upper area, Fig. 6.

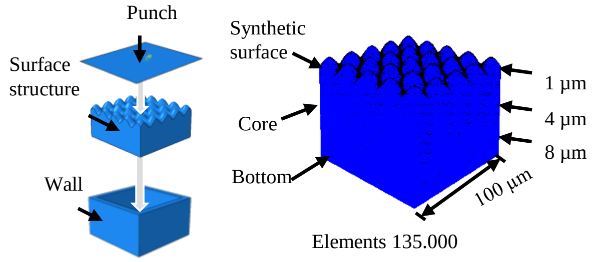

Figure 6: Simulation model composition and meshing graduation of the workpiece

After analyzing the evolving contact area and the resulting contact stresses in Section 3.1 a more detailed view of the friction is performed in Section 3.2. To research the relating friction force a relative movement to the normal punch movement needs to be applied. Therefore a relative velocity of v_{rel} = 40.82 mm/s for the punch was set.

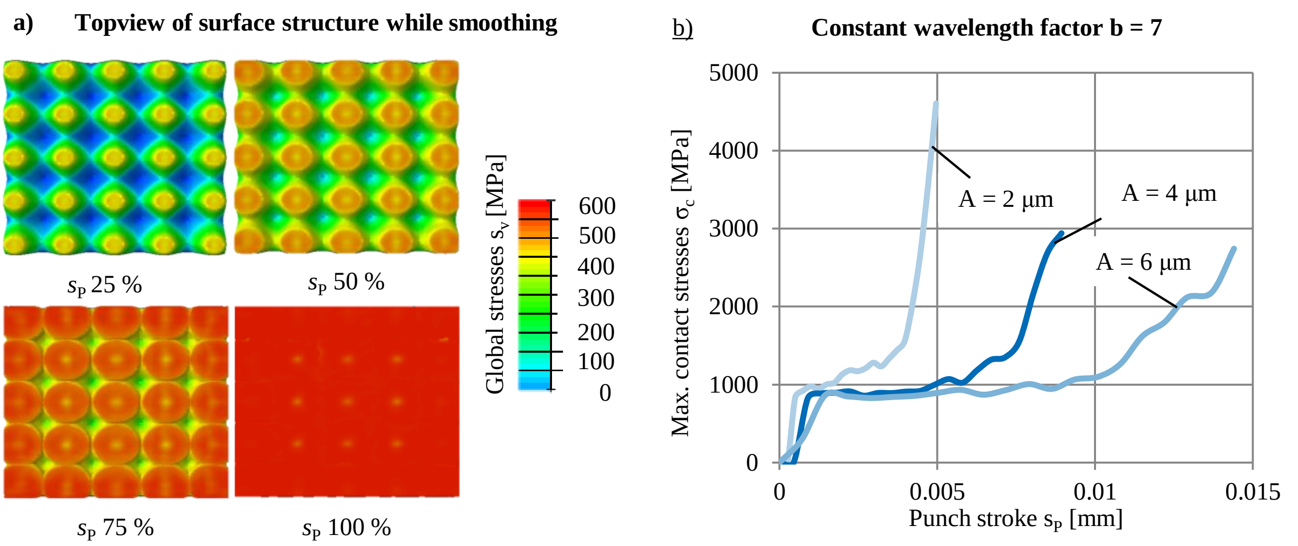

Figure 7: a) Topview on micro model in dependency of punch path and resulting global stresses, b) equivalent diagram of contact stresses over punch path with a variation of wavelength factor b

3.1 Influence of amplitude on contact area, contact stress and friction

A variation of amplitude A and wavelength factor b will be applied. To get detailed results the amplitude will be varied from A = 2 µm over A = 4 µm to A = 6 µm and partially A = 10 µm. Each of these variations

will be carried out for every wavelength factor as these are: b = 5, b = 7, b = 9 and partially b = 17. Thereby, a sufficient detailed overview of practical surface structures can be researched.

Exemplarily the surface with a wavelength factor b = 7 is taken into account to show the mode of action, see Fig 7. The contact area is growing nearly linearly in the beginning and flattens out at the end, when the structure is totally smoothed. The path needed to totally flatten the material is two times the amplitude as by then there are no hills or valleys.

The contact stresses distribution over the punch path occurs in a different way, see Fig. 7(a) s_P = 25 % to s_P = 100 %. After a first fast progression the contact stresses are nearly continuous. They start to grow faster as it nearly reaches the maximum contact area and by that the double height of the amplitude. During that the contact area and the normal force are growing the same. As the pressure is the quotient of normal force and contact area, it remains equal. The exponential growth at the end is caused by an increasing force of 250 %, whereby the contact area just growths by 20 %, see Fig 7 (b). For example the further growth after s_{St} = 0.004 mm with a Amplitude A = 2 µm is irrelevant, because the contact area is already at its maximum and the surface structure is fully smoothened. Thereby it is shown that a lower final contact stress results from a higher amplitude.

At the beginning of the process the contact area is very small, which leads to low initial contact stresses. The force needed to plastically deform the surface is very low as the resistance due to material is low. The more the punch moves into the material, the more material obstructs the movement. Fig. 8 presents a topview of the cut-out part. The same tendencies of contact area and global stresses are visible. The contact area is growing continuously and at the same time the global stresses are getting higher. A small stress gradient persists at the peaks. The maximum stresses are detected at the outer part of the smoothed peaks and not at the center.

The research of the contact area and of the contact stresses is a first step to analyze the surface structure regarding dry forming. These researches are aimed at the detection of friction, friction forces and also the correct friction model. The friction force is a result of a normal force superimposed with a relative velocity. This was realized with each amplitude A and wavelength factor b variation. A constant relative velocity of v_{rel} = 40.82 mm/s was applied to the punch. As seen in Fig. 9 the friction force is higher for lower amplitudes. The force is also progressing faster at lower amplitudes. It can be concluded that for a higher amplitude the force is progressing more slowly and also has a lower maximal friction force, Fig 8.

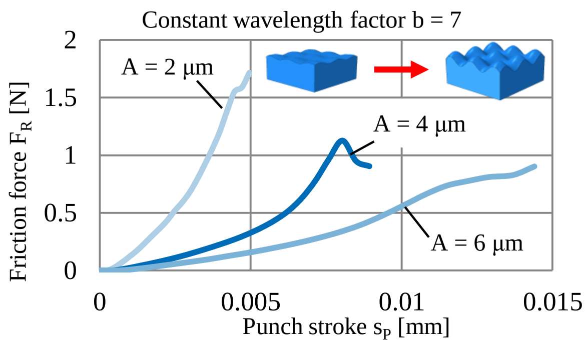

Figure 8: Influence of amplitude on friction force over die path.

3.2 Influence of wavelength factor on contact area and contact stress

As a second factor the distance between each valley has to be investigated. Therefore the wavelength factor b, which influences the number of sinus waves in a certain distance, is varied in the mentioned range.

The wavelength factor variation is presented for a constant amplitude of A = 4 µm, Fig. 9. It shows that the influence of the wavelength factor on the contact area growth is rather small compared to the die path variation. A difference can be detected at the maximum contact stresses. The smallest wavelength factor results in the greatest contact stress.

For the contact stresses the same amplitude A will be taken for analogy purposes, Fig. 9. At the first micrometers the contact stresses are growing nearly equally. At some points they differ slightly but converge again at a later point. The first immanent difference starts at s_P = 7 µm. With a smaller wavelength factor b the contact stresses σ_c start to grow earlier and more progressively. The smallest wavelength factor b has its maximum stresses at σ_c = 4750 MPa, the highest wavelength factor at σ_c = 2550 MPa. So more peaks lead to a lower maximum contact stress than fewer peaks with the same amplitude, Fig 9.

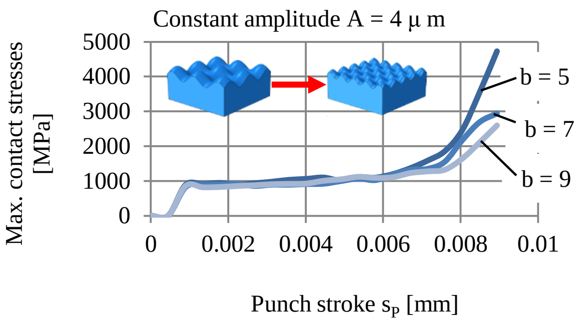

Figure 9: Influence of wavelength factor variation on contact stresses over die path.

The detection of the friction force was also modeled for a varying wavelength factor. As before a constant amplitude of A = 4 µm was modeled. The relative velocity was set again to v_{rel} = 40.82 mm/s. The results depicted in Fig. 10 show the tendency that higher wavelength factors support the friction force reduction. The trends are nearly the same, but it shows that a lower wavelength factor results in lower maximum friction force.

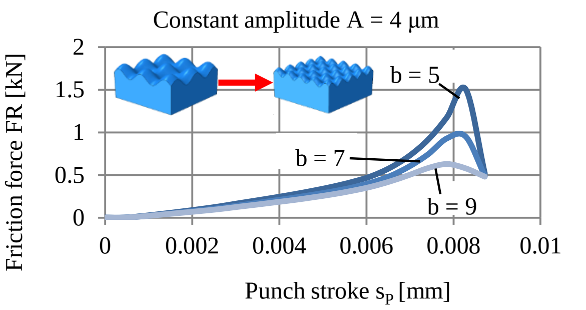

Figure 10: Influence of wavelength factor on friction force over die path.

3.3 Summary

A first approach to research dry metal forming and the effects of the surface structure is the investigation of the surface smoothing on an upsetting process under normal loads. Thereby it can be analyzed how the surface is smoothened and how contact stresses arise. A process with a superimposed punch by a relative velocity gave a first estimation of frictional forces on differently defined surface structures. It helped to get a better process understanding and derived a first suggestion, which friction law should be used in further examinations. With the given results it was possible to distinguish differences in the smoothing velocity and its effects. Compared to earlier modeling approaches it was possible to distinguish a way to reduce computing times, but get a detailed view at the same time on the surface structure. As a shot peened surface structure is stochastic, the actual model needs to be verified to prove its reproducibility. Further on tribotesting needs to be implemented for this simulation model to get information about a comparable smoothing process.

4 Conclusion and outlook

The establishment of dry metal forming could bring new advances to metal forming processes in general and would grant its sustainability, by substitution of lubricants. To reach that aim new approaches in surface structuring of tool and workpiece need to be found. In preliminary works a first process simulation model of the surface structure was generated. Furthermore a novel tribometer was developed to analyze different suitable surfaces for dry metal forming. In a new approach the surface structure was modeled with wave forms resulting of sinus curves. The generated surface structures can be varied by amplitude and wavelength factor b. The influence of these different structures on contact area, contact stresses, smoothing velocity and friction force are summarized, see Tab. 1.

Table 1: Influence of amplitude A and wavelength factor on smoothing velocity, contact stresses and friction force. Legend**:** ◔ symbolizes a degressive, ◑ a linear, ◕ a progressive, and ● an exponential increase. Similarly, means a degressive, a linear, and a progressive and an exponential decrease. ○ Is for a constant value.

An increase of … leads to …	Amplitude A	Wavelength factor b
Smoothing velocity	○	○
Contact stresses	○	◑
Friction force	◔	◕

In further researches these results will enable the determination of the best surface structure. It also needs to be investigated if a change from Coloumb's friction law to shear friction law will support the dry metal forming process or the other way round.

Acknowledgements

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References

[1] F. Klocke: Manufacturing processes 4 – Forming, Springer, (2013).

[2] H. Czichos, K. H. Habig: Tribologie-Handbuch. Tribometrie, Tribomaterialien, Tribotechnik. Springer, (2010).

[3] E. Lugscheider, K. Bobzin, C. Pinero, F. Klocke, T. Massmann: Development of a superlattice (Ti,Hf,Cr)N coating for cold metal forming applications. Surface and Coatings Technology, 177-178 (2004) 616-622.

[4] F. Vollertsen, F. Schmidt: Dry Metal Forming: Definition, Chances and Challenges. Int. J. Precision Engineering and Manufacturing – Green Technology 1/1 (2014) 59–62.

[5] M. Murakawa, N. Koga, T. Kumagai: Deep-drawing of aluminum sheets without lubricant by use of diamond-like carbon coated dies. Surf Coat Tech 76 (1995) 553–558.

[6] M. Murakawa, S. Takeuchi: Evaluation of tribological properties of DLC films used in sheet forming of aluminum sheet. Surf Coat Tech 163 (2003) 561–565.

[7] K. Osakada R. Matsumoto: Fundamental Study of Dry Metal Forming with Coated Tools. CIRP Ann. Manuf. Technol 49/1 (2000) 161–164.

[8] S. Kataoka, A. Motoi. Improvement in DLC thin film adhesion and its application to dry deep drawing. J. Jpn. Soc. Technol. Plast 46/532 (2005) 412–416.

[9] S. Kataoka, M. Murakawa, T. Aizawa, H. Ike: Tribology of dry deep-drawing of various metal sheets with use of ceramics tools. Surf Coat Tech 177–178 (2004) 582–590.

[10] K. Tamaoki, S. Kataoka: Study of deep drawing using diamond coated tools. Journal of Material Testing Research Assoc. of Japan 53/4 (2008) 247–253.

[11] K. Tamaoki, S. Kataoka, K. Minamoto: Dry deep-drawing with use of electroconductive ceramic tools. Proc. Int. Conf. Trib. Manuf. Pro (2007) 175–179.

[12] J. Lin, B. Mishra, J.J. Moore, W.D. Sproul: Microstructure, mechanical and tribological properties of $Cr_{1-x}Al_xN$ films deposited by pulsed-closed field unbalanced magnetron sputtering (P-CFUBMS). Surface and Coatings Technology, 201 (2006), 4329.

[13] N. Bay, A. Azushima: Environmentally benign tribo-systems for metal forming. CIRP Ann. Manuf. Technol. 59/2 (2010) 760–780.

[14] A. Bruzzone, H. Costa, P. Lonardo, D. Lucca: Advances in engineered surfaces for functional performance. CIRP Ann. Manuf. Technol. 57 (2008) 750–769.

[15] P. Mattfeld: Tribologie der zinkphosphatfreien Kaltmassivumformung. PhD-Thesis RWTH Aachen University (2014).

[16] K. Bobzin, T. Böhmermann, S. Bastürk, F.Klocke: Development of an in situ Plsama Treatment of X155CrMoV12 for a (Cr,Al)n PVD Tool Coating for Dry Metal Forming in Cold Forging. Dry Metal Forming Open Access Jorunal (2015) 57-62

[17] D. Trauth, F. Klocke, P. Mattfeld, A. Klink: Time-Efficient Prediction of the Surface Layer State after Deep Rolling using Similarity Mechanics Approach. Procedia CIRP 9 (2013) 29–34.

[18] D. Trauth, F.Klocke. P. Mattfeld, K. Bobzin: Multiscalfe FE-Studies of Contact Stresses of Dry and Lubricated Shot Peened Workpiece Surfaces. Dry Metal Forming Open Access Journal (2015) 11-16