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Microtexturing of cold-forging tools – influence on tool life

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Abstract: Friction and wear in metal-forming processes are dependent on several parameters, including sliding velocity, temperature, material combination, etc. Surface topography also plays an important role. It is evident that so-called lubricant pockets can improve the tribological state. Excimer laser material processing makes it possible to generate such pockets, even on complex-shaped, uncoated as well as coated-forming tools and with flexibility considering the arrangement and geometry of the textures. This paper deals with the investigation of the influence of direct laser texturing of coated tools on tribology in cold-forging processes. The arrangement, size, and geometry of the texture elements were chosen according to results of previous basic investigations. The tribological state is determined by means of industrial tool life tests. The results proved that tool life can be increased significantly, in some cases to more than 300 per cent.

Keywords: cold forging, tool life, tribology, surface treatment, excimer laser, hard coating

1 INTRODUCTION

It is well known that in cold forging the process boundaries, the process stability, and the tool life are linked closely to the tribological state in the forming process that prevails at the contact zone of workpiece and tool. The tribological state determines the wear rate and thus the maximum tool life and the quality of the workpiece. It also determines the friction force that is necessary to enable material flow. To allow the production of very complex parts at low costs, industry demands low friction and low wear in the forming zone. To achieve this and owing to the ancillary conditions in cold forging – high normal pressure, high sliding velocity, and high temperature – it is common to use complex lubrication systems, mostly based on fluids with extreme pressure (EP) additives and pre-treatment of the billets. It is also common to use very expensive high-performance materials such as cemented carbides for the tools that may have additional coating applied.

Friction and wear are very important parameters others include sliding velocity, material properties, normal pressure or temperature. These parameters are significantly dependent on the surface topography of tool and workpiece [1, 2]. The advantage of this is that, in contrast to most of the influencing parameters, which cannot be changed easily as they are process-dependent (e.g. the normal pressure or the increase in temperature at the interface) or owing to economical reasons (e.g. the sliding velocity or the materials), the surface of the tool and the workpiece can be changed in a wide range.

Regarding lubrication, especially liquid lubricants, the surface of the billet and the tool has to transport a sufficient amount of lubricant into the forming zone. At the same time it has to retain enough lubricant to make the formation of hydrostatic and hydrodynamic lubrication effects possible, which enables the lubricant to flow into the contact zone of tool and workpiece and therefore separates both. Another task of the surface is to pick up worn particles and debris (see Fig. 1) [3]. Extremely smooth surfaces as often desired since cold-forging tool surfaces neither support the transportation, storage, and distribution of lubricant nor the transportation of wear particles. In this context an ideal

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Fig. 1 Principle of tribological effects on rough surfaces in metal forming

surface must feature small valleys with a suitable microgeometry in which lubricant can be trapped and must yield a release of lubricant during deformation, hence acting as lubricant pockets [2, 4, 5]. In sheet metal forming it is state of the art to use special textured sheets providing a topography characterized by such more or less defined lubricant pockets that work as desired. In some cases in bulk metal forming the demands on the surface are taken into account by generating a similar texture on the surface of the workpiece by means of shot blasting or other methods. This procedure includes two main disadvantages. First a time-consuming treatment of each single workpiece is necessary and second this effect works at the very beginning of the process only. Owing to the surface enlargement and the strong flattening of the surface in bulk metal forming the lubricant pockets disappear after a short period. In contrast, the tool's surface hardly changes within a single forming step. However, this potential has not yet been utilized since the tool is lapped or even polished in almost all cases.

In addition to the conventional processes of surface finishing, excimer laser material processing particularly provides additional possibilities of surface treatment. Depending on the selected method a modification (of the entire surface) as well as a texturing of the surface (only local material ablation) can be achieved.

This paper deals with the investigation of the influence of excimer laser texturing of hard-coated tool surfaces on their tribological behaviour in cold-forging processes. The effect of microtexturing of hard-coated tools on tool life was investigated by means of industrial test series under conditions of mass production.

2 EXCIMER LASER MATERIAL PROCESSING

Excimer lasers are high-pressure gas lasers emitting pulsed radiation in the ultraviolet (UV) range. In this study a KrF-laser (LPX 315i, Lambda Physik) with a wavelength $\lambda=248$ nm was used. This type of laser has a rectangular beam cross-section that measures few cm^2 and the duration of one single

Fig. 2 (a) Principle of excimer laser material processing with the mask projection technique; (b) surface finishing methods achievable by excimer laser radiation

pulse is in the range of a few 10 ns, which makes it particularly suited for the treatment of surfaces.

The effect on the surface topography that can be achieved depends on the energy density of the laser beam [6]. Material ablation occurs when the energy density reaches the so-called ablation threshold. By varying the energy density relative to this threshold, different methods of surface finishing are possible (roughening, flattening, microtexturing; see Fig. 2(b)). In the range of the ablation threshold, the surface becomes rougher owing to non-uniform ablation because of locally different absorption. Above the ablation threshold the material is ablated homogeneously, leading to a flattening of the surface. Microtextures can be produced by excimer laser radiation with high precision and flexibility. Microtexturing is done at energy densities distinctly above the ablation threshold using a mask projection technique. A mask is illuminated by the laser beam, its geometrical information is projected onto the surface of the workpiece (see Fig. 2(a)) and the irradiated material is ablated. As most of the laser energy is removed immediately with the evaporating material, there is almost no heat transfer into the workpiece and thermal damage is not expected.

3 TOOL LIFE INVESTIGATIONS WITH MICROTEXTURED TOOLS

The overall aim of this paper is the improvement of tool life in cold-forging processes. Tool life depends on wear and friction, which in turn are dependent on several parameters (i.e. sliding velocity, velocity profile, etc.) in a complex way. Since the influence of these parameters is difficult to isolate and investigate by basic experiments, the effect of microtexturing was investigated directly in the press shop of an

industrial partner under conditions of mass production. An industrial process was selected in which tool life is clearly limited by wear and by obviously insufficient tribological conditions, thus being a promising candidate for tool life improvement. The failure analysis of worn-out tools suggests that the wear at the rim (see Fig. 3(b)) can be explained by insufficient lubrication. The tool element in consideration is a punch used in a backwards cup extrusion process for the production of rivets (stainless steel, 1.4567) (see Fig. 3(a)). The punch ($\varnothing=5.2$ mm) is made of high-speed steel and has a TiN-coating applied by physical vapour deposition (PVD) (thickness approximately $2\text{ }\mu\text{m}$). The lubricant used in the process has a viscosity of $100\text{ m}^2/\text{s}$ at 40°C . The tool life achieved with the conventional tool system, which is in the range of some 10 000 pieces, has been monitored for a long period yielding a mean value which is set arbitrarily to $N=1.0$ as a reference. These conventional tools are no longer used, since there is a distinct improvement in tool life possible with MoS_2 -coated tools, which are used today. Therefore, there is an additional reference given by the lives of the MoS_2 -coated tools. This tool lives were averaged for each individual test series, which means that the influence of different material properties in the test series can be neglected.

Fig. 3 (a) Tool and workpiece investigated in tool life tests with microtextured tool surfaces (b) analysis of worn-out punch

A promising texture, concerning tribological and mechanical properties, was identified in basic experiments and adapted to the process presented in [7, 8]. Width and depth of the circular texture elements were set to approximately, $10\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$ (see Fig. 4) according to [4].

Several test series were carried out in the press shop of an industry partner with punches that were microtextured (see Fig. 3(b), left side). The influence of the textured area ratio α , being the ratio between texture elements and the entire area, was varied from 10 to 25 per cent in these investigations. To rule out other effects on tool life, substrate hardness and coating thickness were determined in all test series. The statistical evaluation of tool life is done on the basis of the Weibull distribution (three parameter; as defined in Fig. 5) [9]. It was found that a relative tool life of 81 per cent is a good estimation for the lower bound of tool life $N_{\min}$. Tool life of the microtextured tools and the tools with MoS_2 -coating is summarized in Table 1. Compared with the non-textured tools that were previously used, mean tool life is increased to the relative values of 146 and 177 per cent (see Fig. 5) in the cases of microtextured and MoS_2 -coated tools respectively. That means, there is a distinct improvement in general, but textured tools achieve only 82 per cent of the tool life as it is observed for the MoS_2 -coated tools.

In a second test series, when increasing α from 10 to 20 per cent a further improvement was observed. The effect of this is that mean tool life increases to 183 per cent, even exceeding the MoS_2 reference tool life (which remains nearly constant at 168 per cent, see Fig. 6). In the third series the influence of the textured area ratio $\alpha=25$ per cent is investigated together with a slightly increased textured area. It was extended to the area depicted in Fig. 3(b) on the right side of the tool. The relative tool life is now 132 per cent (see Table 1) in the case of

Fig. 4 SEM-images of excimer laser microtextured TiN-coated tool; left: top view, right: cross-section

Fig. 5 Tool failure probability of microtextured tools ($\alpha = 10$ per cent); N = tool life, $N_{\min}$ = lower bound, N_0 = tool life with failure probability of 63.2 per cent, m = slope (black = microtextured; grey = MoS₂-coated)

Fig. 6 Tool failure probability of microtextured tools ($\alpha = 20$ per cent) (black = microtextured; grey = MoS₂-coated)

Table 1 Results of the tool life investigation in series 1–3; R = coefficient of correlation, yield = $N_{\text{microtextured}}/N_{\text{MoS}_2}$

		Series 1	Series 2	Series 3
Parameters	Area	10 % Small	20 % Small	25 % Large
MoS ₂	N_{mean}	1.77	1.68	1.32
	m	2.73	3.61	2.29
	R	0.97	0.97	0.98
Microtextured	N_{mean}	1.46	1.83	1.31
	m	1.88	1.61	1.26
	R	0.98	0.98	0.98
Yield		0.82	1.09	1.00

the MoS₂-coated tools and it is 131 per cent when microtextured tools are used. That means that the tool lives in general are lower. There is no significant difference between MoS₂ coating and microtexturing. The most important advantage of microtexturing consists of the possibility of adjusting the texture locally to the tribological boundary conditions by varying the geometry and the arrangement of the texture elements.

To summarize the results of all test series, it can be stated that with both measures – microtexturing as well as MoS₂ coating – there is a possible improvement in tool life. The results of tool life investigations in general show a large scatter. Therefore, the tool life of the microtextured tools is not only compared with the long-term average value (which is 1.0 per definition) but it is also compared with the MoS₂-coated tools of the same series which were tested at the same time and process conditions with the same material. In these series the microtextured tools and the MoS₂-coated tools were used alternately. Therefore, the influence of different material or process parameters can be neglected and thus

the ratio of mean tool lives of microtextured and MoS₂-coated tools can be considered as an appropriate parameter to assess the effect of the microtexture. As summarized in Table 1 this ratio (the so-called yield) indicates that the tool life improvement realized by microtexturing may reach or even exceed that of what is possible by MoS₂-coating the tools. As can be seen by the effect of microtexturing parameters, in particular the textured area, there is obviously an optimal parameter constellation, still not definitively identified but worth investigating in future. This also includes the microgeometry of the texture elements, which has a great influence, as shown in reference [2]. In addition, the scatter of tool life is worth discussion too. As can be seen from the Weibull diagram in Fig. 5, and as is quantified by the Weibull exponent m in Table 1, the scatter in the case of microtexturing is higher. This leads to the conclusion that there are lower and also higher values for tool life in the case of microtextured tools. The high values achievable on some tools in turn show the potential of microtextured tool surfaces and indicate what is possible in the future.

As it is evident from the results of series 3 it is not possible to benefit from a further improvement of α , although a higher value of α is equal to a larger volume of entrapped lubricant (see Fig. 7). The reason for this is to be found in the increasing mechanical interlocking between tool and workpiece. Assuming that the punch force is constant when changing the textured area ratio and that the force is transmitted into the workpiece mainly via the residual surface, the increase of α leads to a hyperbolic increase in the normal pressure when the contact area is linear decreasing. Consequently, the material of the workpiece penetrates more and more the valleys of the tool (see Fig. 8). In order to allow a relative movement of the workpiece, the resulting interlocking has to be overcome. The positive effect of microtexturing, which is made possible owing to reduced

Fig. 7 Schematic correlation of lubricant volume and nominal contact pressure versus textured area ratio α

Fig. 8 SEM-image of workpiece produced with a micro-textured tool

friction attributed to a better lubrication, is neglected by this.

The key for a further improvement of the observed results is the application of optimized microtexture geometry. The experiments have shown that even small differences in microgeometry may have a strong impact on the results. It was found that the microtexture of the tools tested in series 3, which have shown a very different behaviour during the test, have a slightly different depth and flank angle. The steeper flanks in the case of the 'bad' tools compared with those of the 'good' tools probably handicap the flow of material as observed in reference [10], resulting in a higher load of the tool. As a result, tool life is not improved as much as can be expected by measure of the texturing. To explain this relationship it is necessary to understand the mechanism of lubrication on textured surfaces. During the forming process the punch force and the contact pressure at the punch face increases permanently. Owing to the high load in the forming zone, the material is pressed into the microtexture elements. The deformation process leads to an enlargement of the surface of the workpiece, which normally produces

Fig. 9 Topography of a used punch and profiles extracted from three-dimensional measurements of workpiece and tool

areas with highly reactive pure metal that tends to adhere, and consequently to adhesive wear. With microtextured tools, which are penetrated by the workpiece material, the surface of the workpiece is enlarged inside the texture elements filled with lubricant and does not react with the tool itself. Therefore the tool is not damaged. Furthermore, lubricant that is stored within the texture elements is squeezed out during the forming process and reduces friction between tool and workpiece outside the microtexture and consequently reduces tool load. In this context it can be stated that the effect of the penetration of the workpiece into the microtexture as observed in this study is very similar to the conventional tribological effective flattening of a lubricated rough surface by a flat tool as investigated by many researchers [2, 4, 11]. Since there is always the disadvantage of the mechanical interlocking, which is a direct consequence of the mechanism, the microtexture's geometry has to be designed well. In order to squeeze out lubricant and considering the contact pressure around the texture elements, the pressure inside the fluid has to be very high. This means that the residual volume between workpiece and tool, with the entrapped lubricant, has to be as small as possible (see Fig. 9). Therefore the depth of the texture should be similar to the penetration depth of the workpiece material. Also the shape of the texture elements has to be similar to the shape of the penetrating material, with flanks that are not too steep. As the flank angle is not equal on all tools under investigation owing to very small inaccuracies of the handling system of the laser system, the results differ significantly. Nevertheless, in general microtexturing is a suitable process for increasing tool life. The volume of entrapped lubricant is higher on microtextured surfaces compared with conventional surfaces. Therefore, the state of liquid lubrication can exist over a longer period. And finally, wear particles are deposited in the texture elements and are

kept inside during the forming process. This means that the length of particles scratching on the tool surface is reduced. As a consequence, the coating is less damaged, yielding an increased tool life. This hypothesis is well supported by the experiments in which a higher textured area ratio α up to approximately 20 to 25 per cent results in higher tool life. Assuming a constant texture element size a higher textured area ratio leads to a higher texture volume (equal to a higher amount of lubricant) and a shorter distance between two textures. It is evident that the wear resistance of the tool surface is an important premise for the performance of the microtexture, as wear would change the microtexture's geometry. The coating investigated in this paper fulfils this premise; accompanying topography measurements and SEM-images have shown that there is a small difference in the tool at the beginning of production and after usage.

4 CONCLUSION

From a tribological point of view, the surface mainly has to store lubricant, to transport lubricant into the forming zone, and to pick up debris. A polished surface is not the best choice since it cannot offer any space for lubricant or particle storage. To improve the tribological properties of the tool surface such a space has to be created. Excimer laser radiation is a tool that is well suited to this purpose. Microtexturing, the local ablation of material, can be used to finish the surface of metal-forming tools as demanded. Microtextures were applied to hard-coated cold-forging punches and tested in the press shop under conditions of industrial mass production. Test series with different textured area ratios α and different textured areas were carried out. The tools with $\alpha = 10$ per cent lead to a relative mean tool life of 146 per cent compared with non-textured tools (MoS₂-coated: 177 per cent). These results were taken into consideration for the design of a second test series with $\alpha = 20$ per cent leading to a relative tool life of 183 per cent (MoS₂-coated: 168 per cent). A third investigation with $\alpha = 25$ per cent and an extended area of texturing was performed and no significant further improvement was obtained. The relative tool life was 131 per cent for microtextured tools and 132 per cent for MoS₂-coated tools. The improvement can be traced back to the fact that lubricant can be trapped in the texture elements and debris is picked up; the tribological conditions in the forming zone are therefore improved.

The potential of laser treatment of tool surfaces is obvious, however has not yet been completely utilized. This technique can lead to higher tool life

that saves material, time and therefore money. However, the transfer of tribological improvement from the lubricant to the surface enables further benefits. The amount of lubricant can be reduced as it is used more effectively. This may make it unnecessary in some cases to apply harmful pretreatment to the billet or additional wash processes prior to welding or painting. Further basic research activities combined with investigations under industrial conditions are necessary to improve the reproducibility of the microtexture's effect and to qualify this technique for industrial use.

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APPENDIX

Notation

m	slope of the Weibull line
N	relative tool life
α	textured area ratio
λ	wavelength of the used KrF excimer laser