THE SELF-FORMING PHENOMENON - DYNAMIC RESTRUCTURING OF TOOL SURFACES IN METAL FORMING PROCESSES

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SUMMARY
A new approach which leads to tool-surface structures with improved tribological properties in metal forming processes is presented. This approach is based on the one hand on an increase of wear resistance and, on the other hand on the general idea to use the remaining wear mechanisms itself for the production of a defined geometrical surface structure during forming (self-forming phenomenon). This effect is initiated by a predefined three-dimensional material structure; i.e. a 3D-surface structure is created out of a 3D-material structure "in situ". In practice, the creation of a defined three-dimensional material structure can be realised by local application of thermal or thermo-chemical surface-treatment techniques (thermal implantation).

Keywords: surface structure, self-forming, thermal implantation, laser alloying, metal forming

1 INTRODUCTION
In metal forming processes, the remaining potential of the tool-surface to improve frictional conditions and wear resistance is not well developed. Generally, it is believed that these structures have to be as smooth as possible in order to avoid interlocking effects between the contacting surfaces, which leads to a higher rate of abrasive wear with increased debris and subsequently to an increased risk of pick up between tool and work piece. Once defined in that conventional way, the geometrical structure should be conserved by material properties, which can be reduced to a maximum hardness criterion. If the hardness of the substrate is not sufficient, additional wear-protective coatings (e.g. PVD, CVD) are applied to achieve higher wear resistance.

![Surface characteristics of conventional tool surfaces](image)

Figure 1: Surface characteristics of conventional tool surfaces

2 TOOL SURFACE DESIGN
2.1 Conventional tool surfaces
As far as no secondary surface functions like transferring a defined structure to the workpiece have to be fulfilled [1], conventional tool surfaces show the typical geometrical characteristics resulting from grinding and/or polishing as last step in the tool production sequence, Figure 1.

![Tribological anisotropy as result of a geometrical anisotropy](image)

Figure 2: Tribological anisotropy as result of a geometrical anisotropy [2]

A common geometrical feature of such surfaces is more or less developed small grooves resulting from the aforementioned mechanical pre-treatment. Under tribological aspects, these unidirectional grooves constitute a geometrical anisotropy, which directly leads to an anisotropic tribological behaviour, Figure 2.

2.2 Ideal tool surfaces
There are two general characteristics of tool surfaces, which mainly influence the tribological behaviour during forming. The resistance against different types of wear and the mechanical stability of microstructural surface elements are defined by the material properties; the interfacial frictional conditions towards work piece and intermediate phase are defined significantly by the geometrical properties. While requirements regarding material properties can easily be reduced to a maximum
hardness and a material based reduction of the cold welding tendency between tool and work piece, requirements on the geometry of tool surfaces only exist in the approach to reduce any present geometrical structure as far as technically and economically possible. However, under pure tribological aspects, general rules for the design of ideal tool surfaces can be postulated in a more defined formulation as follows:

1. a homogeneous distribution of micro contact areas avoids local maxima of contact stress
2. an isotropic network of micro channels facilitates storing and transporting of lubricant and debris
3. the structural extension in vertical direction should be in a submicron range, to avoid wear
4. the structural extension in lateral direction should be in a micrometer range, to increase mechanical stability
5. the material structure in the area of contact leads to an increase of wear resistance
6. the material structure in the area of contact leads to a creation of a diffusion barrier
7. a constant geometry of surface structure during forming leads to a homogeneous process

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Figure 3: Schematic model of tool-surface treatment

### 2.3 Production of defined tool surfaces

According to the schematic model in Figure 3, it is possible to distinguish between uni-, two- and three-dimensional techniques for tool-surface treatment. With pure mechanical techniques it is possible to produce both, geometrically defined surface structures [3, 4] and improved material properties resulting from strain hardening [3, 5]. In the same way, thermal techniques allow to create defined surface structures by local remelting of the tool surface [3, 1] and to achieve an increased wear resistance [6]. However, the maximum hardness level in both directions is determined by the substrate material. Chemical techniques also allow to produce a comparably wide range of different surface geometries [4]. With deposite techniques it is possible to produce surface coatings with extremely high hardness [7] and with typical surface geometries mostly resulting from the polycrystalline morphology of the coating [8]. To improve the properties of these singular treatment techniques, it is possible to apply two-dimensional combinations. Examples of such combined techniques are thermo-chemical surface treatment e.g. by laser alloying or laser dispersing [6] or thermo-deposite techniques such as laser coating [6]. The combination of electro-errosive treatment with shot peening to compensate the evolved white layer constitutes an example of thermo-mechanical treatment of tool surfaces [9]. In the same way, shot peening of coated tool surfaces to influence the residual stress state [10] can be regarded as a mechano-deposite technique. However, what all one- and two-dimensional techniques have in common is the fact, that it is not possible to combine both, geometrical and material surface properties, in an optimised way. Therefore, in the present paper a new technique for tool-surface treatment is introduced, which allows to produce an optimised combination of material properties and surface geometry finally leading to improved tribological conditions during forming. According to the systematic structure of tool-surface treatments in Figure 3, this new approach can be defined as three-dimensional combination of thermal, chemical and mechanical treatment. Therefore, this thermo-chemo-mechanical technique is covered by plane 1-2-3.

### 3 SELF-FORMING BEHAVIOR OF SURFACES

#### 3.1 The self-forming phenomenon

The general idea of aforementioned thermo-chemo-mechanical technique for tool-surface treatment consists in a two-step procedure. In the first step, the material properties are designed towards increased wear resistance and decreased adhesion tendency. However, this is done in such a way that the remaining wear mechanisms can be utilised in the second step to produce defined geometrical surface properties. Therefore, the underlying principle of this method of indirect structuring can be summed up as a self-forming phenomenon. This self-forming effect can be achieved by having a local gradient in mechanical properties, which ensures that wear occurs at different rates in different regions leading to the development of a geometric structure. The gradient in mechanical properties can be created by using known metallurgical treatments. Wear on such a surface with predefined three-dimensional material structure will lead to in-situ production of three-dimensional geometrical structures. Phenomenologically, the process of structural evolution can be divided into three phases. In the initial phase, where a geometrical structure is not yet developed, friction and load conditions are similar over the entire contacting surface. Wear is mainly influenced by the local material characteristics.

It would be expected to be higher in areas with low local hardness and other mechanical properties. This leads to an evolution of a geometric structure in the surface. In the transition phase, different areas in the surface have different geometrical and material characteristics. Micro areas with higher wear resistance remain higher than others and have contact with the work-piece surface. The resulting higher ratio of solid and boundary lubrication leads to predominantly abrasive and adhesive wear mechanisms.
The remaining areas with lower wear resistance, lead to the creation of microchannels, where tribo-chemical flushing and subsequently washing-out effects within the intermediate phase predominate. In the functional process phase, the material properties and loading on different micro areas and structural levels are such that the wear is uniform. The geometric features obtained in the previous phases are maintained over a long functional period. This self-forming principle is explained schematically in Figure 4.

3.2 Thermal implantation

The practical realisation is achieved by thermal implantation of structural areas with a significant higher wear resistance within the overall material structure. For this purpose, the tool surface is locally remelted by a pulsed Laser beam. Simultaneously, extremely fine particles of precoated hard metal carbides are alloyed and/or dispersed into this melting zone [11]. It is important to notice, that the balance of thermal dynamics in the liquid state part of the thermally treated zone, shock wave dynamics from the pulse mode of the Laser, plasma pressure, material loss by evaporation, external material drag-in, solidification shrinkage and geometrical changes resulting from structural transformation in the solid state part of the Laser-treated zone is designed in such a way, that the existing geometrical surface structure is only changed in a submicron range. Figure 5 shows a schematic explanation of this method. The metallographically prepared cross section and top view in Figure 6 show the surface characteristics of a cold work tool steel X165CrMoV12 (1.2601) after thermal implantation of TiC using a Nd:YAG-Laser [11]. The difference in material structure especially becomes obvious by using SEM-microscopy; the different chemical composition of treated and untreated tool surface and, resulting from that, the difference in backscattering behaviour between substrate material and dispersed and/or alloyed TiC in the thermally implanted areas leads to a clear visualisation of the material structure of a thermally implanted surface. Figure 6. By the choice of fraction of dispersed and/or alloyed TiC the hardness of the implanted areas can be adjusted in a comparably wide range.

3.3 Self-forming of real surfaces

Once introduced in a tribological system, the micro-structural system of material properties resulting from a combination between drastically increased hardness of thermally implanted areas and unaffected mechanical properties of the substrate material leads in first instance to the expected system inherent gradient in wear behaviour. According to the aforementioned self-forming phenomenon, a geometrical surface structure evolves from this local wear gradient. This effect occurs under various tribological conditions. However, the extent of the evolving surface geometry depends not only on the predefined material properties, but especially on the specific tribological load profile.

For practical application in cold forming processes, generally two different ways of geometrical structuring by self-forming are possible. Obviously, one possible way consists in a pure dynamic structural evolution and restructuring of the tool-surface by self-forming during forming. However, including not only the functional phase of self-forming, which finally supports stationary process conditions by a constant surface geometry, but also the initial and transition phase, this way of processing consequently consists of a characteristic running-in phase under unstationary conditions.

Therefore, a combination between predefined of an initial surface structure before introducing the tool into the forming process and a dynamic restructuring during forming seems to be more effective in sense of a more homogeneous process. The structural predefined can be achieved directly by the Laser treatment during thermal implantation, or indirectly as a result of self-forming by mechanical pre-treatment, Figure 7. Results of cyclic tests, Figure 8, confirm that self-forming appears under dynamic load conditions as an in-situ mechanism.
The nearly unchanged surface area and at the same time continuously decreasing implant diameter indicates a dynamic restructuring of surface geometry by self-forming under mixed lubrication conditions. Therefore, not only the last in the aforementioned list of postulated requirements on tribological optimised tool surfaces is fulfilled, but also the requirements on geometrical characteristics regarding structural extension in vertical and lateral direction. Generally, a reduced adhesion tendency between tool and work piece can already be expected as a result of the increased fraction of ceramic elements remain as elevated real micro-contact areas in the evolving geometrical structure finally building up the desired diffusion barrier.

4 CONCLUSIONS

A new technology for the design of surfaces to be applied under high tribological load is presented in this paper. This technology is based on the self-forming phenomenon. The practical realisation of this dynamic surface functionality by thermal implantation does not only allow to produce real nanoscaled surface structures on metallic surfaces, but especially allows to achieve a restructuring of the geometrical surface in-situ during processing.

5 REFERENCES