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Microstructuring of cutting punches for tribological optimization of stamping processes

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Abstract
Efficient, cost-effective production requires stable operations and minimal downtime. One such industrially implemented process is the cutting of sheet metal materials in high-performance stamping presses. Key technological parameters – such as cutting gap, cutting-edge design and tribological conditions – are decisive for tool wear and consequently, the resulting quality of the sheared edge. The investigations presented in this paper aimed to reduce wear mechanisms through microstructuring of the lateral surfaces of cutting punches without compromising cutting-edge stability. Reducing the contact area between the punch and the sheared surface can increase tool life quantity and reduce production costs. The primary objective is to develop innovative solutions for demanding industrial applications, e.g. improving tool life when cutting high-strength steels. In a first step, various suitable microgeometries were developed and necessary manufacturing strategies for applying them to the lateral surfaces of cutting punches was derived using a short-pulse and ultrashort-pulse laser system. To analyse and evaluate their effect, the tribological behaviour of the functionalised punches was subsequently investigated in cutting tests. The functionality and enhanced tool life of microstructured cutting punches was successfully demonstrated.

Keywords Laser micro machining, Punching Quality, Stamping, Tribology

1. Motivation and objectives

Punching is a widely used industrial manufacturing technology for the economical production of cut-outs and trimming of sheet metal components [1]. The stresses on cutting punches vary depending on the materials being cut, the cutting geometry and process parameters, particularly the stroke rate and cutting gap [2, 3]. High mechanical and tribological loads often lead to wear, manifesting as adhesion, abrasion and surface damage.

Tool wear directly affects the quality of cut surfaces. If critical limits are exceeded, this can result in inadequate component quality and costly production interruptions due to punch breakage. Therefore, targeted adjustment of the tribological system is an important approach to reducing tool wear and improving component quality in shear cutting. As well as selecting suitable tool coatings and lubricants which must be tailored for the respective sheet metal material, micro-structuring cutting punches is a relatively unexplored way of increasing tool life quantity.

This article presents the different geometrical variants for microstructures introduced to the lateral surface of cutting punches using short- and ultrashort-pulse laser systems. These punches were then examined in terms of their tool life quantity when punching stainless steel strips of alloy 1.4462 on an automatic punching press. The wear characteristics of the structured punches were analysed in comparison to those of reference punches without microstructures.

2. State of science and technology

Innovative approaches to reducing tool wear during shear cutting include designing the punch geometry for a specific purpose, selecting suitable punch materials and using functional coatings. Recently, microstructuring the lateral surfaces of cutting punches has been investigated to improve tribological properties and reduce wear. Studies on surface hammering show that micro-indentations with depths of up to 2.5 µm can lead to a significant increase in tool life quantity, despite a relatively small reduction in contact area of 15–20% [6, 7]. Other microstructuring approaches use pulsed laser systems. Ultrashort pulse lasers are particularly suitable for highly stressed functional surfaces due to their low thermal influence. Laser-based material removal enables a high degree of geometric flexibility and precise control over surface quality [8, 9]. Kitamura reported on the introduction of micro-dimples up to 3 µm deep in TiCN-coated cutting punches using picosecond lasers. These dimples served as lubricant reservoirs and contributed to friction reduction during fine blanking [10].

It is also known that reducing the cutting gap and increasing the cutting-edge radius increases the friction surface and friction forces between the punch and the hole wall [2]. While reducing the contact surface through undercut can reduce the retraction forces. Reduced damping of punch-induced vibrations simultaneously increases the risk of punch breakage. Overall, the current state of research highlights the potential of targeted geometric and surface optimisations to increase the tool life quantity of cutting punches and ensure economical punching processes.

3. Methodology and Validation

3.1 Structural design of microstructures for cutting punches

The development of a methodology for the structural design of microstructures on the lateral surfaces of cutting punches is based on the objective of reducing the contact area between the punch and the hole wall of the sheet metal. It is well understood that a reduction in cutting clearance increases the proportion of smooth cut surfaces, while an increase in the cutting-edge radius leads to a reduction in the resulting hole diameter. Both effects enlarge the frictional contact area and increase the friction force between the punch side surface and the hole wall. This accelerates wear on the punch lateral surface.

Based on this background, various microstructural designs were developed for structuring the punch lateral surfaces in the form of supporting contact geometries. These microstructures enable localized contact between the punch and the hole wall, allowing defined regions of the punch to slide along the wall. This design ensures adequate stabilization of the punch during the cutting process while simultaneously reducing the effective contact area. An overview of the investigated structural variants is presented in Figure 1.

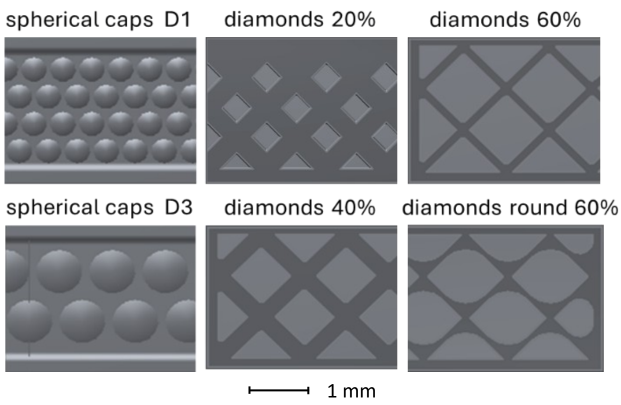

Figure 1: Overview of the developed structural variants

The spherical cap structure was derived with the aim of maintaining the punch guide within the hole wall at specific points with as little surface area as possible. The diamond structure and its variants were developed with the aim of maintaining continuous lateral, flat support through the remaining webs. This is expected to result in less local wear. In the derivation of the round diamond structure, all corners are rounded in the axial punch stroke direction so that potential material removal cannot collect in the structure corner and cause damage. The distance between the microstructure and the cutting edge was set to 0.3 mm for all punches. The percentages shown in Figure 1 indicate the degree of contact surface reduction. The target for the diamonds was a reduction in surface contact of between 20 and 60%. For the spherical caps D1 and D3 this is initially 84%. With increasing wear, the degree of contact area reduction for the smaller spherical caps D1 (four-row) decreases more rapidly than for the spherical caps D3 (two-row). For example, wear of 15 µm for spherical cap D1 resulting in a reduction of the circumference corresponds to a remaining contact area reduction of 58.8%, whereas spherical cap D3 exhibits a value of 62.4%.

The structural design was based on the sheet thickness of 0.8 mm to be cut and the process- and machine-dependent penetration depth of the punch into the sheet material. As illustrated in Figure 2, an unstructured region is located adjacent to the cutting edge, followed by a structured region. Depending on the structure configuration and the punch penetration depth, this structured region has a height of approximately two to three times the sheet thickness. The height of structuring area and the unstructured area constitutes the effective range. Together with the punch circumference, it defines the developed surface area to be structured. The distances between individual structures, web widths, and structure dimensions were calculated using a custom-developed Excel tool and optimized with the Solver add-in integrated in Excel.

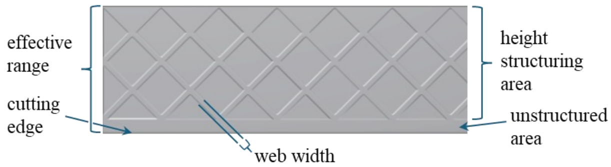

Figure 2: Overview of structural design

The optimization criterion was the maximization of the reduction in the targeted contact area. In addition, the developed surface length of the rhombic, rectangular or round punches served as the basis for calculating the structure distribution.

All shaped and round punches used as test specimens were manufactured from Vanadis 23 (SPM23) powder-metallurgical high-speed steel (material numbers according to EU standard: 1.3395 (1.3394)). This steel grade is widely used in industrial applications for machining stainless steels and spring strips and is characterized by high toughness, good wear resistance, and low hardness distortion. The punch geometries employed in the experiments are shown in Figure 3.

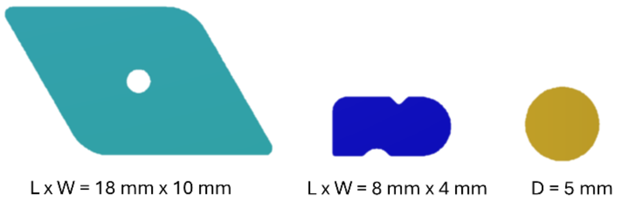

Figure 3: Punch shapes from left to right: rhombus-shaped cutting punch, rectangular cutting punch, round punch

The following analysis of the test results focuses on the wear behaviour and achievable tool life quantity of round punches with a diameter of 5 mm. These punches were manufactured using a short-pulse laser system to investigate possible changes to the boundary layer of the punch material caused by short-pulse laser processing. This issue primarily arises when processing with short-pulse lasers, which are still widely used in industry.

3.2 Microstructuring of cutting punches

The microstructuring of cutting punches comprises three main steps. First, the optimum material removal parameters for the cutting die material are determined to maximize the cost-effectiveness of the additional machining process with respect to the achievable extension of tool life quantity. To this end, the laser power, pulse frequency and duration, feed and line distance were varied, and in ten parameter combinations were examined for ablation characterisation. (Figure 4)

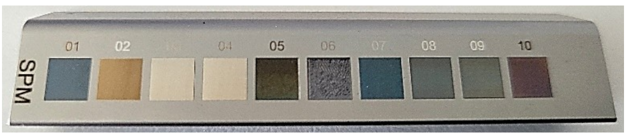

Figure 4: Test fields for ablation characterisation by laser parameter variation

The selection of suitable machining parameters represents a trade-off, as high ablation rates and low surface roughness constitute competing objectives. To evaluate the individual parameter combinations, the initial surfaces of reference punches were measured using a confocal microscope (MarSurf CM mobile). The determined roughness values served as reference and comparative metrics for the assessment of the test fields.

In the second step, a suitable fixture for holding the cutting punches in the laser system's machining unit was designed and manufactured according to the respective die geometry. For round punches, a concentric fixture is sufficient, as the laser focal position remains unchanged during rotation. For non-rotationally symmetric punch geometries, such as rhombic or rectangular shapes, however, eccentric positioning may be required. In these cases, the laser focus must be maintained by repositioning the laser head, which may adversely affect the achievable structural accuracy.

The third step involves adapting the structural specifications to the respective punch geometry and mounting configuration. First, the developed surface length is determined, and the microstructure to be applied is subdivided into defined individual segments. While only a single segment is required for round punches, the developed surface of rhombic punches is divided into multiple segments to ensure reproducible structure transfer.

Figure 5: Example for division of the punch shell surface into 16 sub-segments to structure the rhombus punches

The calculation of the segment division is illustrated using the D1 spherical cap structure as an example. For the structuring process, the segment length, the angular position of the indexing device and the Z-position of the laser head are calculated and programmed as positional parameters for each segment. The structure segments are implemented as negative geometries in STL format.

To transfer the structural variants, three-dimensional negative developments were generated for each structure using a CAD program and subsequently applied to round punches with a diameter of 5 mm as well as to shaped punches. Measurements of the fabricated microstructures confirmed that the specified minimum structure depth of 35 µm was achieved. Minor deviations toward greater structure depths do not affect the punching process, as the effective contact area reduction remains unchanged. Although the project successfully demonstrated that microstructures shown in Figure 1 can be applied to complex punch geometries shown in Figure 3 and offer practical advantages when cutting different material classes, the discussion of the results below is limited to round dies. This allows us to illustrate the fundamental mechanisms of action using their simple geometry.

3.3 Experimental validation

The cutting punches manufactured in the described manner were used in experimental investigations. An automatic punching press BRUDERER BSTA 510-150B2 was used for the systematic cutting tests using a set of three punches from each microstructure family. The specific structure used was determined in preliminary tests thus choosing spherical caps D1, diamonds 40% and round diamonds for the experimental validation. Experience-based, the targeted test duration was set at 200,000 strokes. The press operated at a rate of 350 strokes per minute. Additionally, reference tests were carried out with round punches without microstructured outer surfaces. Strips of corrosion-resistant stainless steel 1.4462 (X2CrNiMoN22-5-3) with a tensile strength of 800 MPa and a sheet thickness of 0.8mm were cut.

It was demonstrated that the lifetime of cutting punches can be positively affected by microstructuring. In the reference test, none of the six punches used achieved the target of 200,000 strokes. On statistical average, the reference punches achieved a tool life quantity of 74,800 strokes, with a minimum value of 15,500 strokes and a maximum value of 150,000 strokes. In contrast, all punches of the three structure variants investigated achieved a tool life quantity of 200,000 strokes. The cutting tests were then continued beyond the initial target. Here, it was found that the microstructured cutting punches all exceeded a tool life quantity of 275,000 strokes. The use of microstructured cutting punches thus led to a significant increase in tool life quantity which contributes to fewer production interruptions and thus higher productivity. This enables an economical use of these cutting punches despite the increased manufacturing costs associated with microstructuring. [11]

The cutting forces differ only slightly between the reference punches and those with microstructures. In contrast, a significant reduction in retraction forces was achieved, which can be regarded as an indication of improved tribological conditions, particularly during punch retraction.

Figure 6 shows microscope images of the three structural variants examined, each at 0 stroke and after 200,000 strokes. In addition, the best performing reference punch is shown at 0 stroke and after 150,000 strokes. The latter one shows significant pitting on the cutting edge.

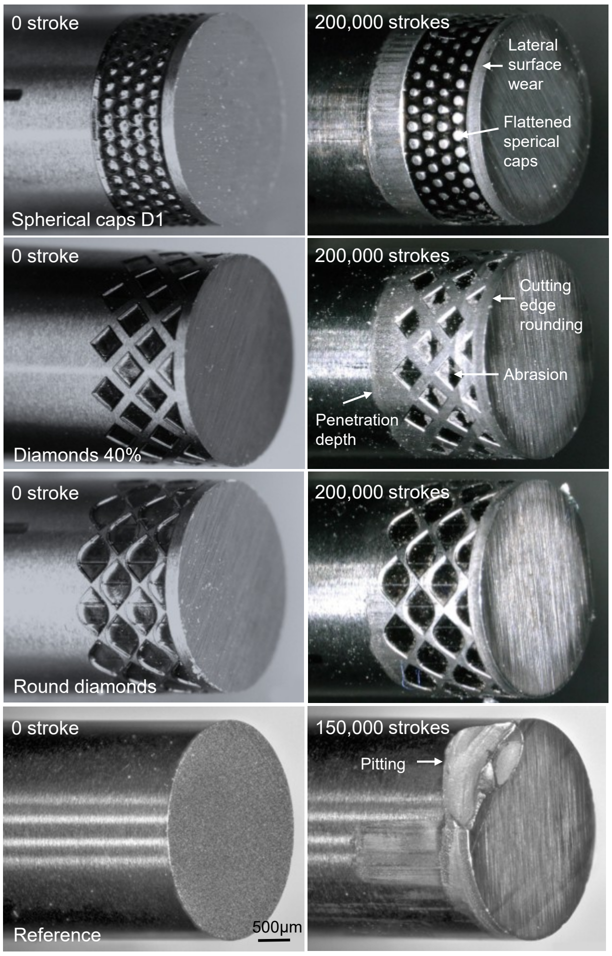

Figure 6: Comparison of cutting punches

All punches show an increase in cutting edge rounding as the number of strokes increases. Punches with the spherical cap structure variant D1 show wear on the front area of the outer surface. The spherical caps are significantly flattened, which means that abrasive wear has occurred. As a result, the contact area between the punch and the hole has increased again over the course of the test. In the diamond structure variant 40%, the microstructure appears sharp-edged and has a metallic sheen in the pockets. As the test progresses, there are hardly any noticeable changes to the microstructure. A certain amount of wear is also evident on the front area of the outer surface. It is noticeable that after 200,000 strokes, a considerable amount of abrasion has accumulated in the pockets of the microstructure. This is probably due to a kind of filing effect caused by the sharp corners of the rhombuses. However, such phenomena cannot be observed with the round diamond structure variant. No changes to the microstructure are visible here. The extent of wear on the cutting edge is like that observed with the other two structure variants. All punches were measured regarding their cutting edges using a 3D-MicroCAD system. This measurement shows a reduction in punch diameters of approximately 15 µm. The microstructures on the dies were partially measured and evaluated using a Mahr Surf Mobile before and after the tests. Due to the extensive measurement data and complex test matrix, the results can only be discussed in general terms.

Technologically, each of the three structural variants examined offers certain advantages and disadvantages, particularly in terms of specific wear behaviour and the specific progression of retraction forces. However, all three structural variants significantly increased tool life quantity compared to the reference, highlighting the great potential of this adaption of the punching process. Taking all the relevant criteria into account, the round diamond structure variant is recommended for the cutting task under review, as it exhibits the least wear after 300,000 strokes. Whether these observed advantages result primarily from the reduced retraction forces is subject of further research. When adapting the cutting task, it is advisable to review the selection of the structural variant (considering the sheet thickness and material properties of the sheet metal to be cut), and to test it in field trials, if necessary, before putting microstructured cutting punches into industrial use.

4. Economical uses of microstructured cutting punches

The cost-effectiveness of surface-adapted punching tools largely depends on their manufacturing costs and the tool life quantity achieved during the punching process. The manufacturing costs of structured cutting punches include the material costs of the punch as well as the set-up and production times of both the punching press and the laser system. Laboratory tests have shown that the manufacturing costs of a microstructured cutting punch are approximately 2.5 times higher than those of a reference punch.

Tests conducted at Fraunhofer IWU demonstrated that using structured punches resulted in an almost quadrupled tool life quantity. Despite the initially higher tooling costs, this results in an overall cost saving of approximately 35% compared to the reference test. [11]

5. Summary

Microstructuring of cutting punches offers the potential to optimise cutting processes tribologically and increase the achievable tool life quantity. As part of the research work presented, various microstructures were developed which were introduced into the outer surfaces of cutting dies by laser ablation. In continuous cutting tests, it was demonstrated that this can significantly extend the achievable tool life quantity while maintaining the same cutting surface quality. It was shown that the economical use of such dies is even possible if the dies are manufactured under laboratory conditions. A significant increase in tool life quantity was achieved compared to non-structured reference punches. The results illustrate the potential for tribological optimisation of punching processes using microstructured cutting punches. Furthermore, it was shown that processing with a short-pulse laser system has no negative impact on the tool life quantity of the structured cutting punches. Various improvements in a prospective industrial and further automated microstructuring process can further reduce the costs of punch production considerably. This includes further optimisation of the ablation parameters of the short-pulse laser with the aim of achieving shorter processing times, i.e. accepting slightly higher roughness levels in exchange for faster ablation. Alternatively, the use of a femtosecond laser also offers the potential for shorter structuring times. The set-up times in the laser system can be significantly reduced by using devices for fast and reliable mounting of the cutting stamps. This enables a further reduction in costs and an increase in the economic advantage resulting from the use of tribologically optimised cutting punches.

Acknowledgements

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