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Localized dispersing of TiB₂ and TiN particles via pulsed laser radiation for improving the tribological performance of hot stamping tools

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Abstract

The aim of this study is to increase the tribological performance of hot stamping tools by using a laser implantation process. This technique allows the fabrication of separated, elevated and dome-shaped microfeatures on the tool surface in consequence of a localized dispersing of ceramic particles via pulsed laser radiation. Hence, the topography and material properties of the tool are modified, which influences the tribological interactions at the blank-die interface. However, an appropriate selection of ceramic particles is an essential prerequisite, in order to obtain tailored and highly wear resistant surface features. In this regard, different titanium-based hard particles (TiB₂ and TiN) were laser-implanted on hot working tool specimens and subsequently tested by means of a modified pin-on-disk test regarding to their wear and friction behavior.

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1. Introduction

In the automotive industry, lightweight construction of modern car body components has become a key strategy in order to face the strict greenhouse gas emission and safety regulations set by the government. In addition, growing customers' demands for electrically powered vehicles have encouraged the importance of lightweight construction even more. By substituting commonly used steel grades with ultra-high strength steel (UHSS), the weight and thus the energy efficiency and range of the electric car can be enhanced without affecting its crashworthiness. However, high-strength materials are characterized by limited formability and large springback, which in turn requires the application of temperature-assisted forming operations [1]. In this context, hot stamping has been established as suitable and resource efficient process for manufacturing geometrical complex and high-strength components with superior dimensional accuracy. Hot stamped

parts are usually made out of boron-manganese 22MnB5 steel sheets, which are initially austenized and subsequently formed and quenched simultaneously by means of a water-cooled die. However, these cyclic thermo-mechanical loads promote the occurrence of high friction and severe wear at the blank-die interface, which in turn negatively affects the workpiece quality and the tool lifetime. Although various methods for reducing the tribological load have been investigated, such as applying a solid MoS₂ lubricant [2] or utilizing an AlCrN tool coating [3], no long-term economic or environmental-friendly benefits have been achieved. The laser implantation technique is a promising new approach for reducing the tribological load within hot stamping. This method combines the surface texturing and the optimization of the material properties in a single process step by embedding ceramic particles into the tool surface via pulsed laser radiation. As a result, separated, elevated and dome-shaped microfeatures are created, which influence the contact area and thus the tribological interactions between tool and

workpiece. However, a suitable selection of hard ceramic particles is a crucial prerequisite, in order to generate tailored and highly wear resistant surface features. Therefore, different titanium-based (TiB_2 and TiN) materials were laser-implanted in hot working tool specimens. The resulting geometrical shape and mechanical properties of the laser-generated microfeatures were analyzed and compared, in order to gain in-depth knowledge about the particles dispersion behavior. Afterwards, modified pin-on-disk tests were carried out for qualifying the effectiveness of the surface modifications. In this regard, conventional as well as laser-implanted tool surfaces were tested under hot stamping conditions for evaluating the wear and friction behavior of both tooling systems.

2. Methodology

2.1. Laser implantation process

The laser implantation technique is based on a localized dispersing of pre-coated tool surfaces by using a pulsed laser radiation. The principle of this technology is shown in Fig. 1.

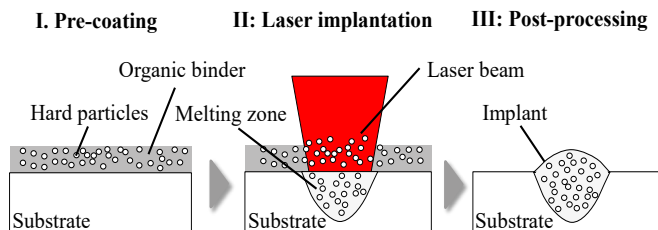


Fig. 1. Scheme of the laser implantation process.

The substrate material is pre-coated with an organic binder and the ceramic particles. Afterwards, the pre-processed surface is locally treated by using a pulsed fiber laser, which in turn leads to a volume increase in micrometer range caused by the finely dispersed particles. In the post-processing step, the remaining coating is removed from the substrate. For the experimental procedure, the hot working tool steel X38CrMoV5-3 (1.2367) with a hardness of 602 HV1 has been chosen, which is commonly used for industrial hot stamping applications. As implantation material, titanium diboride (TiB_2) and titanium nitride (TiN) powder has been selected. The properties of these particles are listed in Table 1.

Table 1. Properties of hard ceramic TiB_2 and TiN particles

Properties	Titanium diboride (TiB_2)	Titanium nitride (TiN)
Grain size	5.3 μm	3.2 μm
Hardness	3480 HV1	2450 HV1
Melting point	3225 $^\circ\text{C}$	2950 $^\circ\text{C}$
Structure	Hexagonal	Cubic

Both kind of materials offer a great potential for improving the tribological performance of highly stressed tool surfaces due to their ceramic properties and high melting temperatures, which are beneficial to reduce the amount of adhesive wear as well as to resist thermo-mechanically alternating load conditions. However, the created microstructures must provide a defect-free metal matrix composite with a high share of homogeneously disturbed particles in order to gain a high wear resistance. For this purpose, all surface features were produced with a specific set of parameters, which guarantee high process reliability. The hot working tool specimens were covered by a coating

thickness of $100 \mu\text{m} \pm 10 \mu\text{m}$, containing the ceramic particles and Mowital 30 H as an organic binder. After drying on air for 24 h, the pre-coated surfaces were treated by a pulsed Yb:YAG fiber laser with a wavelength of $\lambda = 1070 \text{ nm}$ and a Gaussian intensity profile. The laser implantation process was carried out by using a pulse power of $P_p = 90 \text{ W}$, a pulse duration of $t_p = 9 \text{ ms}$ and a spot diameter of $d_s = 105 \mu\text{m}$. This means that each implant was treated with an intensity of $1,04 \times 10^6 \text{ W/cm}^2$ and a pulse energy of 0.81 J (or fluence of 9354.4 J/cm^2). Argon was used as protective gas (22 l/min). After the laser treatment, ethanol was utilized as solvent to remove the remaining coating from the surface. The implants were created on flat tool pin topographies in an area of 5 mm in diameter. All microfeatures were arranged in a hexagonal pattern within a spot distance of $750 \mu\text{m}$. Prior to the tribological experiments, the geometrical and mechanical properties of the resulting structures were measured via white light interferometry and Vickers hardness measurements. Additionally, the particle-matrix interaction was studied by scanning electron microscopy (SEM) and X-ray diffraction (XRD) to explain the mechanical properties.

2.2. Tribological investigation

A modified pin-on-disk test was used for qualifying the wear behavior and friction coefficients of conventional and laser-implanted tool surfaces under hot stamping conditions (Fig 2). The wear test rig is based on a heated metal support, in order to maintain a homogenous temperature and secured clamping of the blank. In addition, a tool pin (length $l = 70 \text{ mm}$, diameter $d = 22 \text{ mm}$) has been mounted on a frame and attached to the kinematic robot of type Kuka KR200-3 for applying a defined load and sliding velocity on the heated workpiece. Inside the pivoted frame, a precisely calculated combination of weights has been installed at the bottom, in order to ensure a consistent load transmission during the tribological experiments. The applied normal force F_N and friction force F_R was permanently quantified with four integrated load cells of type C9B (HBM). Consequently, the friction coefficient μ could be calculated according Coulomb's law ($F_R = \mu \times F_N$). Prior to experimental procedure, the contact area of all mounted tool pins was controlled by means of a pressure indicating film (Fujifilm prescale) to ensure a uniform pressure distribution at the blank-die interface. Afterwards, an AlSi coated 22MnB5 sheet metal (depth $d = 1.5 \text{ mm}$, length $l = 200 \text{ mm}$, width $w = 34 \text{ mm}$) was austenized for 360 s at $930 \text{ }^\circ\text{C}$ in an external oven and subsequently placed on the testing apparatus. Then the tribological experiment was carried out within three consecutive steps.

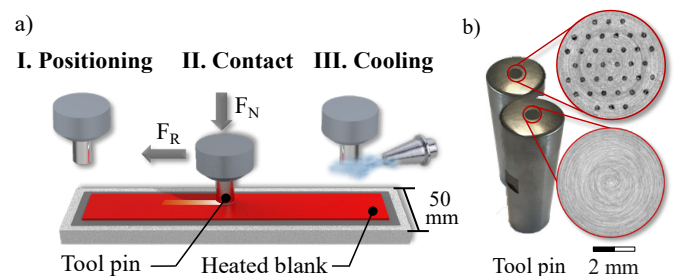


Fig. 2. (a) Modified pin-on-disk test for analyzing the tribological behavior of (b) laser-implanted and unmodified tool surfaces.

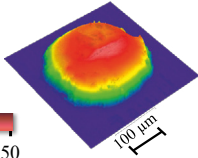
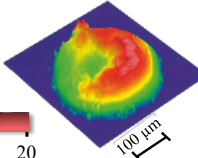
Initially, the pin is positioned and moved onto the heated blank. While the tool slides over the workpiece in a second step, a constant normal force F_N is applied. Finally, the surface of the pin is cooled by compressed air, in order to consider the thermal alternating stress of an industrial process. All tool configurations were tested with three pins and five blanks, resulting in a total wear track distance of 6750 mm. The experiments were conducted with a sliding velocity of $v = 120$ mm/s, a contact pressure of $p = 10$ MPa and a blank temperature of $T_B = 800$ °C, in order to imitate industrial hot stamping conditions. Before and after the modified pin-on-disk tests were performed, the contact area of the tool pin was analyzed via optical measurement to evaluate the wear development. In this regard, the unworn and worn profiles of the tool surfaces were superimposed by using the software program VK Analyse-Modul for quantifying the volume difference and thus resulting the amount of wear.

3. Results and Discussion

3.1. Laser implanted tool surfaces

The resulting geometrical and mechanical implant properties are shown in Table 2. In both cases, dome-shaped structures are created, which are characterized with different implant heights. In this regard, it is assumed that titanium nitride is more likely to dissolve during the laser implantation process, since TiN particles reveal a 275 °C lower melting point and a 2.1 μm smaller grain size in contrast to TiB₂. As a result, microfeatures with reduced dome height are generated since all laser parameters were kept constant within both experimental procedures. However, by varying the laser parameters (pulse power, pulse duration, spot diameter), a precise adjustment of the implant shape (diameter, elevation and penetration depth) can be expected, which in turn was investigated within further studies [4]. By comparing the mechanical properties, high hardness values of over 1500 HV1 were obtained for TiB₂ implanted zones, whereas the implantation of TiN leads to a hardness drop of ~ 200 HV1 in contrast to the initial conditions.

Table 2. Resulting geometrical and mechanical implant properties

Properties	Titanium diboride (TiB ₂)	Titanium nitride (TiN)
Hardness	1525 HV1	407 HV1
Diameter/Height	$\sim 262 \mu\text{m} / \sim 40 \mu\text{m}$	$\sim 259 \mu\text{m} / \sim 20 \mu\text{m}$
Geometry		

To explain these differences, the particle-matrix interaction was studied by SEM and XRD measurements. Fig. 3 shows SEM-BSE images of the implanted zones in top-section. In both cases a defect-free microstructure with dispersed primary and precipitated secondary particles is visible. The latter one indicates a partial dissolution of some primary particles. The retained austenite (γ_R) contents of the implants were determined by XRD-measurements (Fig. 4). No γ_R was detected for the initial substrate material and only a slight share was found for TiB₂ implants. Therefore, the very high hardness

values of TiB₂-based microstructures can be addressed to the dispersed primary particles, the precipitated secondary particles and the martensitic matrix [4]. In contrast, a very high γ_R content of $\sim 33\%$ was detected for TiN implants. Since γ_R is a very soft phase and the overall implant hardness is dependent on the share of the hard particles in the matrix, the observed hardness drop is reasonable.

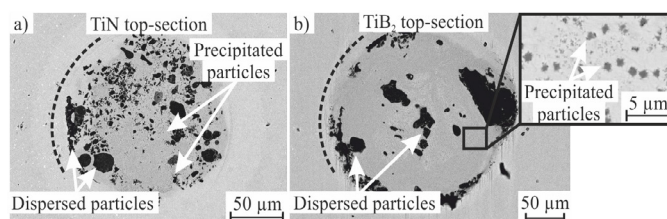


Fig. 3. SEM images of a single TiN (a) and TiB₂ implant (b).

The γ_R formation can be described as follows: (I) The laser treatment leads to an alloying of the molten material with C and Cr from the matrix and Ti, B or N from the dissolved primary particles. (II) During solidification some of these elements form secondary particles (Fig. 3). (III) However, since the cooling rate is very high for pulsed laser treatments, some of the alloying elements remain within the matrix and cannot be precipitated. (IIIa) In the case of TiB₂ this leads to a hardness increase since boron is known as hardening element and does not stabilize the austenitic phase. (IIIb) In the case of TiN a hardness decrease occurs, since nitrogen stabilizes the austenitic phase [5]. Therefore, higher γ_R contents and lower hardness values must be expected. Thus, the implant hardness is not only determined by the particles intrinsic properties, but especially by their interactions with the matrix, if they have been dissolved.

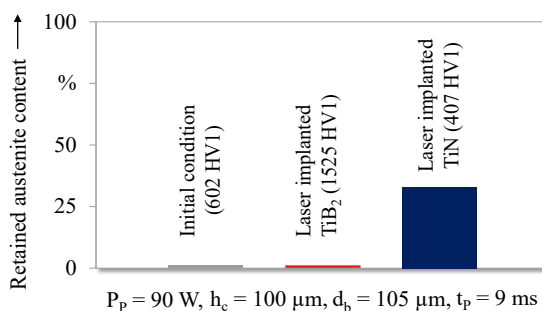


Fig. 4. Retained austenite content for different material conditions.

3.2. Tribological impact

The tribological impact of the laser-generated surface features was qualified via modified pin-on-disk tests. The measured mean friction coefficients and corresponding roughness profiles of the worn blank topographies are illustrated in Fig 5. By using conventional tool surfaces, an average friction value of 0.469 ± 0.020 was identified. In contrast, decreasing friction forces were achieved by means of both laser-implanted tool configurations. Basically, this effect can be explained by the significant reduction of the contact area between tool and workpiece, which in turn results in a declining amount of frictional shear stresses during the relative movement of the pin. By comparing both modified surfaces, an improved tribological behavior could be detected for TiN-based microfeatures due to their favorable geometrical and mechanical properties. In this context, titanium nitride is more likely to

dissolve during the laser implantation process, which allows the creation of implants with reduced height and hardness. Consequently, the penetration depth of the microstructures into the austenized and therefore softened workpiece decreases, which in turn results in reduced frictional shear stresses during the tool movement. To verify these cause-effect relations, tactile measurement (Perthometer MarSurf XR 20) according to DIN 4776 were performed for analyzing the roughness profiles of the worn blanks. The measurements were repeated three times perpendicular to the wear tracks, to consider statistical deviations of the worn blank topography. The comparison of both laser-implanted surfaces reveals that decreasing R_a as well as R_z values and thus penetration depths were obtained by utilizing TiN-based microfeatures, which in turn is in accordance with the assumed friction mechanism. Compared to unmodified tool surfaces, an increasing plastic deformation of the workpiece is identified by means of TiB₂ implants, which diminish the tribological benefit of the reduced contact area.

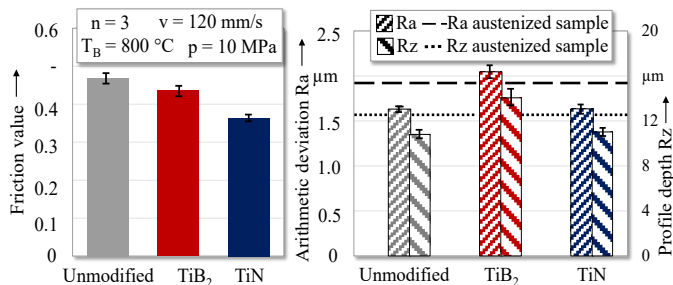


Fig. 5. Friction coefficient and roughness value of the worn blank.

For evaluating the wear development, the contact zone of the tool was investigated by means of optical measurement. Fig. 6 depicts the computed wear volumes after testing each configuration with $n = 3$ pins. All surfaces exhibited adhesive wear layers, which were sheared off from the coating of the softened blank due to the tool movement. This wear effect can also be observed in industrial hot stamping applications [6]. However, the amount of tool-sided wear was significantly decreased by using laser-implanted tool surfaces. It is assumed that the dome-shaped microfeatures are leading to a reduced mechanical interlocking of the roughness peaks at the blank-die interface. Hence, less wear debris are sheared off from the austenized and therefore softened workpiece. In addition, the high wear resistance might also be promoted by the ceramic properties of the finely dispersed particles, which in turn diminish the chemical affinity to adhesive wear. In this regard, ceramic materials tend to be less prone to adhesion since the amount of metallic bonding forces is significantly reduced at the blank-die interface [7].

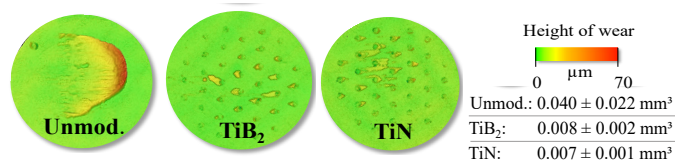


Fig. 6. Measured wear volumes of the tool surfaces.

4. Summary

As a new approach, the named laser implantation process has

been investigated, in order to improve the tribological performance of hot stamping tools. This technique is based on a localized dispersing of hard ceramic particles by pulsed laser radiation, which enables the formation of separated, elevated and highly wear resistant microfeatures. In this regard, different titanium-based (TiB₂ and TiN) particles have been embedded into hot working tool surfaces and subsequently analyzed with respect to their resulting geometrical and mechanical properties. The experiments reveal that both materials enable the generation of a defect-free metal matrix composite with a high share of homogeneously disturbed particles. By using the same set of laser parameters, but different hard particles, however, different mechanical and geometrical properties were identified. In particular, a higher proportion of TiN particles was dissolved in the melt due to their decreased grain size and melting temperature, which resulted in implants with reduced height and hardness values. To evaluate the tribological impact of the surface features, modified pin-on-disk tests have been performed under hot stamping conditions. In this regard, laser-implanted tools exhibited a significantly higher wear resistance and reduced friction coefficients in contrast to conventional tool topographies due to the limited contact area as well as the high fraction of finely dispersed ceramic particles, which abate the formation of adhesive wear. By comparing both kind of modified surfaces, reduced penetration depths and frictional shear stresses were obtained by using titanium-nitride-based microfeatures due to their favourable geometrical and mechanical properties. In future studies, these investigations will be intensified by varying the laser parameters and the hard phase composition, in order to achieve tailored geometrical and mechanical properties for enhancing the effectiveness of the surface engineering technology.

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