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RESEARCH

Tribological and Thermal Investigation of Modified Hot Stamping Tools

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A B S T R A C T

Direct hot stamping is an established manufacturing process to produce safety-relevant car body components, while t-he hot blank is formed and quenched simultaneously in a water cooled press. In order to protect the semi-finished parts against oxidation the surfaces are coated with aluminum silicon. As a side effect this coating system leads to adhesive wear on the tool surface, which reduces the tool life. Due to the high temperatures it is not possible to use lubricants as wear protection. For this reason a suitable surface modification for hot stamping tools is required to increase the wear resistance. In the scope of this study the tribological behavior of different modificatiosn is investigated. The main purpose of these wear protective layers is to decrease the adhesive wear on the tool surface. The wear characterization is carried out with a modified pin-on-disc test. During the experiments the pin is guided over the blank with a robot system. In addition, the contact area is cooled after each wear track to simulate the thermal alternating stresses of the hot stamping process. For the evaluation of the wear behavior a new developed analysis method is used, which enables the calculation of the adhesive and abrasive wear volume.

1. INTRODUCTION AND STATE OF THE ART

Increasing demands regarding strength, stiffness and crashworthiness are in conflict with lightweight designs. One of the main issues in the automobile industry is to ensure a high level of passenger safety in the event of a crash. Due to the increasing demands regarding new car emission standards, the manufacturers are working on new applications for modern cars to reduce the weight of body components and dangerous contaminations like carbon dioxide.

Hot stamping was developed to combine those requirements. This manufacturing process is an established technology of forming high-strength steel grades [1]. In industrial applications two main variants were developed. While the indirect method is commonly used in order to produce more complex shaped parts, direct hot stamping is utilized for car body parts with a small drawing depth [2]. The basic principle in both processes is identical. First of all, the blanks are austenitizated over 900 °C for several minutes. Afterwards, the semi-finished parts are formed and quenched simultaneously in water-cooled tools [2]. The main difference between both technologies is the sequence and the number of the necessary process steps. In indirect hot stamping the parts are formed up to 90 % of their final geometry at room temperature before they are heat-treated and hardened. In direct hot stamping the parts are formed and cooled at the same time. The workpiece surfaces are exposed to high thermal stresses. For this reason the blanks are coated with aluminum silicon to avoid oxidation [3]. A disadvantage of this protective layer is that it leads to adhesive wear on the tool surface. The tool life is decreased and a time and cost consuming rework of the hot stamping tools is necessary to ensure a constant part quality. Due to the high process temperatures it is not possible to use lubricants as a wear protection. The scope of this study is to investigate and describe the correlation between different new surface modifications and the resulting wear behavior. In addition, the wear resistance of hot stamping tools will be increased by identifying the necessary element concentration of an innovative protection layer.

Several test equipments are available in order to study the wear development for different surface modifications under industrial relevant conditions. Common pin-on-disc test setups consist of a rotational disc in a heating chamber, which ensure an examination at elevated temperatures [4]. In this regard, the sheet is heated up over 900 °C for austenitization in the chamber. After the heat treatment the workpiece is cooled down to the target temperature. The pin is positioned with the required load on the disc, which rotates below the tool for a certain time. Afterwards, the pin is moved out of this furnace and is cooled with an air nozzle [4]. Reciprocating friction and wear testers are also commonly used to examine the tribological conditions in hot stamping [5]. During the experiments an upper tool oscillates against a stationary disc. This movement is controlled by an electro-magnetic drive. An implemented cartridge heater of the lower specimen holder enables a heating of the disc up to 900 °C. The temperature, the stroke, the applied load and the frequency of the oscillatory movement are measured through the tests [5]. Further test rigs for wear and friction analysis are hot strip tribometers [6]. In these test setups a blank is austenitizated and positioned in a clamping device. An upper friction jaw is pressed against the heated workpiece during the experiments, while the blank is drawn under the jaw. The normal and friction force is measured to calculate the friction coefficient [6]. In some of these test setups the tool is not exposed to thermal alternating stress, which occurs in hot stamping. In other devices the pin is in contact with the blank surface during the entire test period. For an analysis under industrial relevant conditions, it is necessary that new material of the sheet material is always in contact with the tool and the contact area is cooled.

Conventional characterization of the surface wear is based on determining the wear rate. The tool weight is measured before and after the experiments in order to evaluate the abrasive and adhesive wear. In this regard, a weight lost is caused by abrasive wear while an increase of the tool weight is the result of a layer build-up on the surface caused by adhesion. An EDX analysis can also be carried out to verify if material was transferred from the workpiece to the tool surface. [4] It is also possible to qualify the abrasive and adhesive wear by measuring the tool topographies [7]. However, for a more detailed evaluation of the surface wear of different materials, a quantification of the amount of wear is necessary. An analytic method was developed to determine the wear volume of partially worn specimens for microforming technology [8]. An unworn area of the contact area is used as reference to set a critical wear limit as three times of Sa, which is necessary to avoid an influence of high grooves and deep valleys in the profile height while calculating the wear volumes. The areas above the wear limit are identified as adhesive and the areas below this parameter as abrasive wear [8]. This procedure is not possible for an analysis of the wear behaviour in hot stamping since adhesive and abrasive wear occur during the deep drawing process at the same time. For this reason, an advanced algorithm for calculating the wear volume of the tool surface is necessary.

In this study, the wear and thermal behaviour of new surface modifications are analysed and evaluated. In the first step, the influence of varying element composition of the surface modification on the tribological condition of hot stamping tools is investigated. In order to examine the surface wear, a new developed analytical method is used to determine the wear volume. Unlike the evaluation program for microforming, the measured roughness data are aligned to each other. The friction behaviour is also studied to verify if constant tribological requirements are present. In addition, a rapid cooling after modifying the tool surfaces has to be ensured to guarantee a phase transformation from austenite to martensite and therefore the high mechanical strength of hot stamped parts. For this reason, the thermal conditions are ascertained for the different modified tool surfaces. In the last step, the application of the surface modification with the highest wear resistance will be tested under industrial relevant conditions in a deep drawing process. First of all, the high stressed areas are identified with a numerical simulation. In this regard, the distribution of the contact pressure along the die radius is analysed. The tool topography of an unused and used die is measured to compare the profile height with the numerical results. The aim of this method is to correlate the surface stress with the resulting wear behaviour. In addition, a local surface modification of the wear critical areas can also be realized by this investigation. In the last step, experimental analysis will be carried out to verify the effect of modified surfaces on the tool life.

2. EXPERIMENTAL SETUP

2.1 Specimens

Due to the increased thermal alternating stresses, which occur during the hot stamping process, the tools must have advanced temperature strength, high toughness and a pronounced thermal shock resistance. The standard tool steel is 1.2367. Compared to cold work steels, the chromium, molybdenum and vanadium contents commonly increase the wear and temperature resistance of hot work steels [9]. The special steel WP7V is increasingly important in the industry, which was developed as an alternative to 1.2367 in order to increase the wear resistance [10]. Since both tool steel grades tend to high adhesive wear, they are used as substrate materials for the tested specimens in this study.

The tool surfaces are modified by laser alloying [11] or coating. In this regard, WP7V is primarily used for the laser alloying process, as it is already high-alloyed especially with chromium. In this study it has to be ensured that even those steel grades can be reliably modified by the laser alloying method. As main alloying elements Ti, Mo, Cr and C were selected since they are transition metals with a lower density of moving electrons than metals and consequently the tendency to metallic adhesion can be reduced [12]. For the experiments an Yb:YAG fiber laser was used with a nominal output power of 1 kW and a wavelength of 1070 nm [11]. The alloying process was performed at 500 W, while the clamped specimen on a sledge was moved with an axis speed of 6 mm/s under the laser beam [11]. The wire was guided into the process using a feeding unit FD 100 LS-WB by DINSE with a constant speed of 0.2 m/min. The chemical compositions of the substrate [13] and filler wire materials [14] are shown in Table 1.

Table 1. Chemical composition of the materials.

Chemical composition (wt%)	Ni	C	Cr	Mo	Ti
Substrate material					
WP7V	-	0.5	7.8	1.5	-
1.2367	-	0.38	5.0	3.0	-
Filler wire material					
Mo	-	0.1	-	0.5	-
NiMoCr90	2.1	0.1	0.5	0.5	-
308L	10	0.02	20	-	-
316L	12	0.4	18	3.5	-
AX-312	9	0.12	30	-	-
1.3348	-	0.9	4	8.5	-
SG2Ti	-	0.07	-	-	0.1

An alternative wear protection layer was produced with Physical Vapour Deposition (PVD). These coating systems have a sufficient thermal resistance. In this regard, AlCrN and AlCrTiN consist of the required properties and have a coating thickness of approximately 2 µm. For this reason, they are examined regarding their wear behaviour and compared to the alloyed surfaces. The coating process was performed in a vacuum chamber, where the material is evaporated and deposited on the substrate. Argon is introduced in the chamber with a flow rate of approximately 800 ml/min and plasma is generated by applying a voltage of typically 200 V [15]. The ions collide with the coating material and particles are removed. These elements settle on the contact area of the base material and the layer grows atom by atom. The coating process is carried out at 450 °C [15].

In direct hot stamping boron-manganese steels are used as sheet material with an aluminium-silicon pre-coating. This protective layer has an eutectic composition with approximately 88 % aluminium, 9 % silicon and 3 % iron. The layer thickness is between 25 µm and 30 µm [16]. Compared to the austenitization temperature, aluminium has a considerably lower melting temperature of 660 °C, so that a liquid phase is present [17]. During the heating process iron diffuses from the substrate material into the surface coating, resulting in intermetallic phases of iron-aluminium-silicon. Due to the formation of iron rich phases, stable bonding of Al_8Fe_2Si is present, which results in an increasing solidification of the coating system. Consequently, the temperature resistance is increasing [17]. The content of silicon of the layer reduces the rapid formation of brittle iron and aluminium phases. On the blank surface aluminium forms with oxygen an aluminium oxide layer, this results in a high oxidation protection [16].

The high strength steel 22MnB5 is the most common used material for the semi-finished parts. Before the austenitization the blanks have a ferritic-pearlitic microstructure with yield and tensile strength of 400 MPa and 600 MPa [1]. During quenching the austenitic structure transforms into martensite, which results in an increase of the yield and tensile strength up to 1100 MPa and 1600 MPa [1].

2.2 Testing procedure

Modified pin-on disc test

In this study the wear behaviour of different surface modifications will be characterized with a modified pin-on disc test. In order to increase the wear resistance of hot stamping tools different element concentrations were applied on the tool surface. Compared to conventional wear test rigs the thermal alternating stress is taken into account, which is caused in hot stamping due to the insertion of the hot blank sheet and the subsequently quenching of the part in the tool. In addition, this experimental setup has an open tribological system, which allows a continuous flow of new sheet material into the contact zone. The construction consists of a kinematic robot of the type Kuka KR 200-3 on which a tool frame is attached. A heating ring is mounted around the pin holder and creates a maximum temperature of 550 °C in the pin. The normal force of the tool on the sheet is adjusted via the tool frame. After austenitization, the blank material is positioned on a moveable slide with two ceramic heating elements. A blank temperature with a maximum of 850 °C can be realized.

Before the experiments, the required normal force is measured using a 10 kN load cell of the type C9B. For this purpose, the robot positions the pin on the measuring device. This procedure ensures a precise adjustment of the force. After the setting of the normal force and the heat treatment of the workpiece material, the robot moves the pin with the applied normal force over the hot blank. Due to the relative movement between the pin and the sheet metal, the slide is pressed against a 1kN load cell, which measures the frictional force. Three 2 kN load cells of the type C9B (Co. HBM) are implemented under the slide, in order to monitor the normal force during the tests.

In order to investigate the wear behaviour under process relevant conditions the chosen process parameters are common to industrial standards. The testing procedure is divided into three steps, starting with the positioning of the pin on the blank surface with the required normal force. In this study a force of 196 N was applied in order to achieve a contact pressure of 10 MPa for a contact area of 5 mm in diameter. In the next step, the robot moves the pin with a sliding speed of 120 mm/s for 50 mm over the sheet metal material. Since the movement of the robot is also divided into an acceleration and deceleration phase, it is necessary to detect the range of the constant speed. In this regard, the motion sequence of the robot was measured with ARAMIS Professional 2018 from GOM, which is a non-contact and material-independent measuring system. ARAMIS provides accurate 3D coordinate displacements, speeds and accelerations of the test equipment. The measurement of the velocity distribution showed that the sliding velocity for a wear track of 50 mm is constant for 30 mm. These adjustments are close to conditions of industrial forming processes of hot stamped car body components. After each wear track the contact area of the pin is cooled by compressed oil free air to ensure a thermal alternating stress like in the hot stamping process. One tool pin is used for a total wear distance of 1250 mm, which is divided in 25 wear tracks of 50 mm length each. The blanks have a dimension of 200 mm length, 30 mm width and 1.5 mm thickness. The pin has a length of 70 mm and a diameter of 22 mm. Due to a flat contact area of 5 mm it is possible to measure the entire worn area, which is required to evaluate the wear development.

Hot strip drawing test rig

The friction behaviour is analysed with a hot strip drawing test rig. Compared to the previous setup the friction jaw has a contact area of 47 mm x 52 mm, so it is more difficult to analyse the surface of the whole contact area. However, the advantage of this system is that the experiments can be performed at even lower contact forces, which is due to the construction of the pin-on-disc test not possible. In order to verify if the tribological conditions are comparable to the hot stamping process, a determination of the friction coefficients on a sample basis is sufficient. For this reason, the experiments were performed only for some surface modifications. The selection for this analysis was based on the results of the pin-on-disc tests and was therefore made for the variants with the highest wear resistance.

A heatable friction jaw and a heatable sledge are installed. After austinization of the workpiece, the blank is positioned on the heating elements of the sledge to ensure a constant temperature of 600 °C. The investigation was carried out under these thermal conditions to ensure that undesirable wear mechanisms do not influence the tribological behaviour and consequently valid friction coefficients are determined. A thermographic camera measures the surface temperature of the sheet metal to validate the thermal conditions. The normal and drawing forces are applied by two hydraulic cylinders and are measured by piezoelectric force sensors. A hydraulic power unit provides the necessary energy to apply the required forces. A maximum normal force of 10 kN is applied on the blank surface, that correspond to a contact pressure of 5 MPa. A drawing velocity of 120 mm/s is adjusted by the hydraulic actors. During the tests the blank is drawn underneath the tool. The relative motion occurs exclusively between the upper side of the sheet metal strip and the friction jaw. The described process parameters were chosen to ensure a determination of valid friction coefficients.

Quenching

The purpose of the quenching tests is to verify if a high cooling rate is reachable after modifying the tool surfaces. The high strength of the hot stamped parts results due to a transformation of an austenitic into a martensitic structure during the hot stamping process. A high quenching speed has to be ensured by the tool contact to achieve martensite. For this reason, the heat transfer is investigated. Especially, a surface coating can influence the thermal interaction between the tool and the blank. For the determination of the heat transfer a quenching tool with two exchangeable contact plates was used. After the austenitization process, the specimens are positioned on three spring seated pins to avoid a rapid cooling of the surfaces. The blanks have a sheet thickness of 1.5 mm and are equipped with thermocouples to measure the temperature curve during the experiments. In the quenching plates heating cartridges are inserted. Since the tools are heated up to an average of 150 °C during the hot stamping, which results due to the positioning a hot blank in the forming tool and the rapid cooling of the component during the process, the cooling behaviour was examined at this surface temperature. The experiments were carried out in a hydraulic press type Lasco 100 So. A normal force of 92.8 kN is applied on the workpiece. For an area of 160 x 58 mm^2 this value corresponds to a contact pressure of 10 MPa. The measured temperature profiles were used to identify the cooling rate for different surface modifications.

Deep drawing test

The transferability of the surface modifications concerning model geometries were proven in a cup deep drawing test. For this purpose the protective layer were chosen, which consists of the highest wear protection in the pin-on-disc tests. Compared to conventional methods the high stressed areas are determined with a numerical and experimental analysis. In the first step, a simulation model was created and validated with measured force-displacement and temperature curves of formed cups. The distribution of the contact pressure along the die radius was numerically calculated to identify the area with the highest load. In addition, 200 cups were formed and after the tests the modified and unmodified tool surfaces were measured with a laser-scanning microscope. By determining the surface roughness and topographies, the areas with the highest material adhesion of AlSi particles are located. These measurements were correlated to the analysed distribution of the contact pressure along the die radius. Based on this procedure, it is possible to evaluate the influence of the tool modification on the tool life. The experiments were carried out with the hydraulic press Lasco 100 So. The die diameter is 59 mm and has a hardness of 54 +1 HRC. The punch has a diameter of 50 mm. Both tools have an edge radius of 10 mm. The tests were carried out at the maximum speed of the press at 50 mm/s and at a tool temperature of 150 °C. In order to avoid a rapid cooling of the blank, a spacer ring of 3 mm thickness is used. A scheme of the deep drawing test is given in Fig. 1.

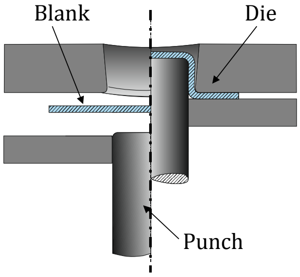


Fig. 1. Deep drawing test.

3. WEAR CHARACTERIZATION METHOD

For the wear characterization of differently modified tool surfaces a further developed analysis method is utilized. Previous analyses are limited to qualify the wear behaviour with the determined surface roughness or the tool topography. However, for an evaluation of the wear resistance of hot stamping tools a quantification of the resulting surface wear is necessary. For this reason, an algorithm was programmed in Matlab R2013b to calculate the adhesive and abrasive wear volume of worn surfaces. The contact area of the specimens is measured with a laser-scanning microscope before and after the experiments. Using the evaluation program of the microscope the profile heights are aligned and the size of the evaluation range is determined. This procedure is required, to ensure that an identical dimension of the measuring data is used for the calculation of the wear volume. In the case of an inclined or curved surface, the measuring range is aligned with a plane or a 2nd degree polynomial by regression. In the next step, the position and height data of the measured contact areas are exported as asc.-file and imported into the programmed script of Matlab. The algorithm scans the measurement data line by line and column by column and the profile heights of a worn and unworn tool surface are adjusted to each other. For the wear characterization it should be noticed, that the surface wear will only occur within the contact area. Since this section is a circle with a diameter of 5 mm, but also areas outside this circle are included in the determined data, it is necessary to exclude them for the analysis. Using the circular formula, these areas are separated from each other in the algorithm. For the evaluation of tool wear, the profile height of the worn and unworn contact area is compared. For this purpose the roughness data have to be aligned to each other, which requires a reference height *h*. The distance between the areas outside the contact surface is used to position the profiles one above the other. This procedure enables the calculation of the wear volumes by subtracting the graphs from each other and the sum is determined. Since the result of this calculation can be positive or negative a critical wear limit is set automatically in order to differ between the abrasive and adhesive wear volume. If the sum is negative, the result is evaluated as abrasion because wear particles are broken out of the surface. If the value is positive, the material adhesion causes an increase in the height profile. The analysis method is also illustrated in Fig. 2.

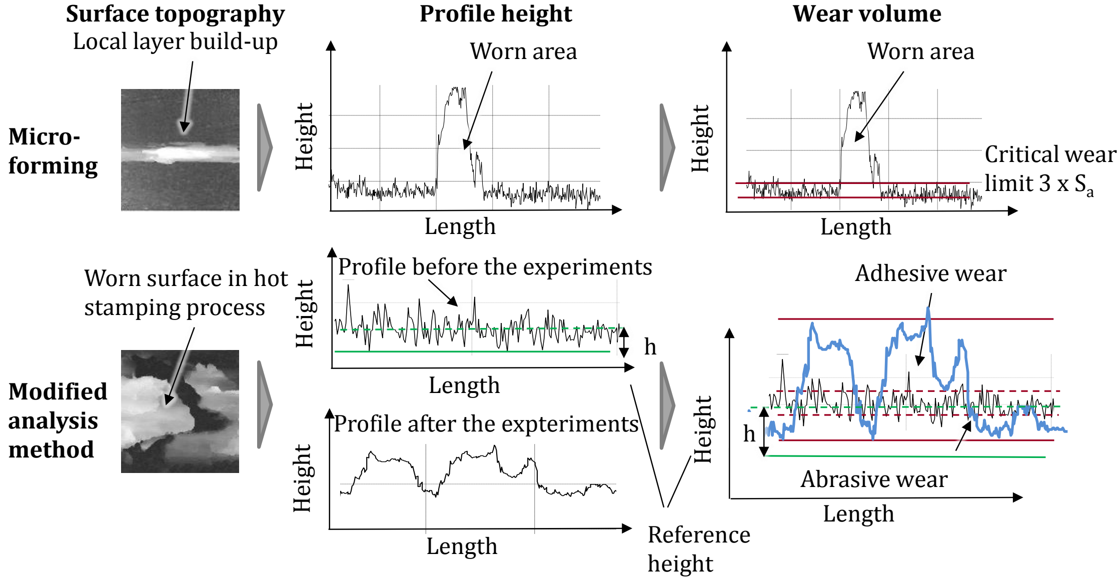


Fig. 2. New wear analysis method for the evaluation of the wear behaviour.

4. RESULTS AND DISCUSSION

Wear behaviour

In order develop a suitable wear protection for hot stamping tools, different surface modifications were investigated regarding their wear behaviour. Since WP7V is already high alloyed, the solubility or chemical bonding of the filler elements with the base material must be ensured. For this reason, this tool steel grade was primarily used for the laser alloying modification. The wear behaviour of the tools was investigated with an adapted pin-on-disc test. For the evaluation of the wear resistance by using different modified tool surfaces, the abrasive and adhesive wear volume was calculated with the new analysis method. The results are illustrated for an unalloyed and for the alloyed substrate material WP7V in Fig. 3.

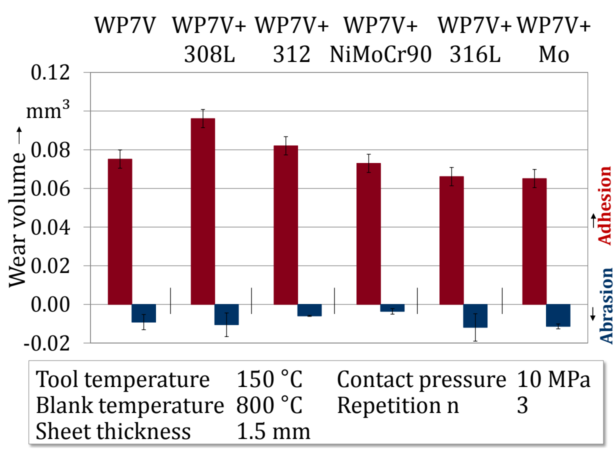


Fig. 3. Wear behaviour of different alloyed surfaces.

The influence on the wear behaviour of the main alloying elements nickel, chromium and molybdenum with a different chemical composition was examined. These are important material components in order to increase the corrosion resistance of conventional tool steel grades [18]. However, it has not yet been investigated whether these elements can be used to improve the wear resistance of press hardening tools. Based on the calculated wear volumes shown in the diagram, it can be seen that adding nickel to the substrate material leads tendentially to a higher adhesive wear on the tool surface. Compared to the unalloyed WP7V a significant reduction of adhesion could not be achieved with the chosen filler wire materials. In particular, the samples alloyed with 308L and 312 have the highest wear deposits. These filler wires have also a high nickel content of 10 wt.% and 9 wt.%. While the determined adhesive wear volume for 308L is 0.096 mm^3, this value for 312 is 0.082 mm^3. Both results are above the wear quantity of the WP7V, which have an amount of 0.075 mm^3. According to the examination of the tribolgoical behaviour of electroless nickel coatings the dominant wear mechanism of theses tool surfaces is adhesive wear [19]. This might be due to a larger density of moving electrons, which favour the formation of new metal bonds. For the modification four filler wire materials with different amount of nickel in combination with chromium were chosen to investigate the influence of these elements on metallic adhesion. The chosen material composition of 308L with a nickel content of 10 wt.% and 20 wt.% chromium does not reduce the chemical bonding forces between the tool surface and the AlSi coating of the blank during the frictional contact. For this reason, an increase of adhesive wear on the tool surface is the result. Compared to 308L, modifying the tools with 312 tends to reduce the surface wear, which is possibly caused by a threefold higher proportion of chromium than nickel. This element might have a lower chemical affinity than the nickel content. Fildes et al. [20] examined the wear behaviour of different hard coating systems. In their study, they verified that a diamond chromium coating consists of a higher adhesive and abrasive wear resistance than a nickel boron protection layer [20]. Based on these results, it is possible to reduce the tendency to metallic adhesion by adding a significant higher chromium concentration than nickel into the substrate material. Considering the calculated wear volume for the alloyed surfaces with 312, chromium is needed in order to decrease the adhesive wear. Since the substrate material WP7V consists already of 7.8 wt.% chromium, saturation behaviour occurs and no significant increase of the wear resistance can be achieved with this element. For this reason, an even higher addition of chromium is necessary to decrease chemical affinity of the tool surface. The specimens, which were modified with NiMoCr90, have similar wear behaviour like WP7V. In this filler wire material the amount of nickel and chromium is decreased, while molybdenum is added. Unlike 312 the adhesive wear can be reduced with NiMoCr90. Due to these results, it is necessary to decrease nickel in the substrate material and to use molybdenum as alloying element. In order to confirm this assumption 316L with a similar nickel and chromium ration than 308L and an addition of molybdenum was used. This material composition results in a higher wear resistance of the modified tools. The determined volume of the adhesive wear is with 0.066 mm^3 lower than for 308L. This amount of wear is only slightly lower than for NiMoCr90, which has an adhesive wear of 0.073 mm^3. In addition, 316L consists also of a higher carbon proportion than all the other used filler wire materials. Since carbon is a none metal, this element is less prone to adhesion and therefore the chemical affinity between tool and blank is further decreased with 316L. The experiments of the modified surfaces with Mo indicate that molybdenum for tool steel grades in hot forming operation should be increased to ensure a sufficient wear resistance. In summary, the additives chromium, molybdenum and carbon are necessary in order to increase the wear resistance of hot stamping tools. For this reason, further investigation were carried out with 1.3348, which consists of 0.9 wt.% carbon, 4 wt.% chromium and 8.5 wt.% molybdenum. It also does not contain any nickel.

The filler wire material SG2Ti was also chosen for the next investigations. In addition, some specimens were coated with AlCrN or AlCrTiN to determine which surface modification consists of a higher wear protection. The calculated results are illustrated in Fig. 4.

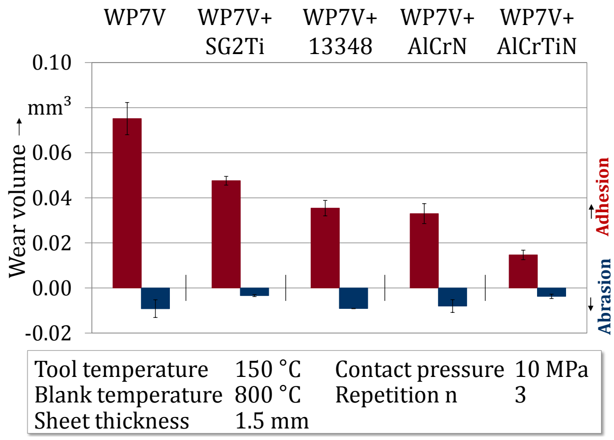


Fig. 4. Characteristics for alloyed and coated surfaces.

The wear volume of modified tools with SG2Ti was decreased by 36 %. Since the metallic adhesion is strongly dependent on chemistry of the interacting material, the additional content of titanium by using the filler wire SG2Ti reduce the bonding forces between the tool and the AlSi coating of the blank. The electron density of the hot working steel is decreased, which result in a formation of fewer new metal bonds and consequently less material transfer [12]. The alloyed pins with 1.3348 have comparable wear behaviour than the tool coating AlCrN. Unlike the substrate material WP7V these surface modifications reduce the adhesive wear of approximately 50 %. While the main alloying elements chromium and molybdenum of the wire material 1.3348 are transition metals, the carbon content is a non-metal element. The combination of these components reduces the chemical affinity between the tool and the blank. In addition, carbon consists of a different lattice structure than metals, which further decrease the adhesion tendency [12]. It can also be assumed that molybdenum favours the formation of primary carbides. Fontalvo et al. [21] proved in their studies that the carbide content in the tool surface and the distance between the individual carbides have a significant influence on the adhesive wear behaviour [21]. Due to their study the layer build-up can be reduced by increasing the carbide content, while reducing the distance between the carbides. However, these experiments were carried out at room temperature. For this reason, further investigation regarding an increase of the adhesive wear resistance for hot stamping tools is required.

Compared to the alloyed tools the coated surfaces have a higher potential to increase the wear resistance of hot stamping tools. The chosen PVD coating systems are commonly used as wear and oxidation protection in machining [22]. Due to the high cutting temperatures the tool surfaces have to resist increased thermal load. For this reason a coating system is required, in which no crack formation occur caused by the induced mechanical and thermal load during the manufacturing process. In this regard, the tool coatings AlCrN and AlCrTiN can be used for applications at elevated temperatures [23]. The combination of aluminium and titanium leads to a solution strengthening, which result in an increased coating hardness [22]. These mechanical and chemical properties of AlCrN and AlCrTiN are required for the application for hot stamping tools. However, the wear behaviour of these layers, in particular for hot forming tools, has not been sufficiently investigated. According to Çöl et al. [24] coated punches with AlCrN for sheet blanking have a higher wear resistance than uncoated surfaces [24]. In their study they were able to proof, that the predominant wear mechanisms are adhesion and abrasion, which is similar to the wear behaviour in hot stamping. Compared to the blanking process higher thermal stress occurs during hot forming. However, the results in Fig. 3 show that it is possible to increase the wear resistance of hot stamping tools. The wear volume is 55 % lower than the calculated value of the uncoated specimens. The addition of titanium even reduces the surface wear by 80 %, as can be seen for the modified tools with AlCrTiN. This result confirms the assumption, which was made for the alloyed surfaces with SG2Ti. The titanium content increases the wear resistance due to a lower chemical affinity between the tool and the AlSi coating of the blank. In summary, the highest adhesive wear resistance can be achieved for coated tool surfaces with AlCrTiN.

The applicability for the conventional hot work steel 1.2367 was also investigated. In this regard, the surface modification were chosen, which showed the highest wear protection in the previous experiments. The wear volumes are illustrated in Fig. 5 for 1.2367, alloyed tools with 1.3348 and coated pins with AlCrN and AlCrTiN.

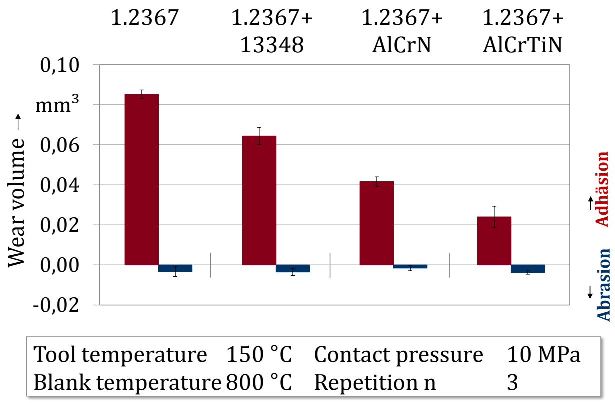


Fig. 5. Application for conventional tool steel grade.

The wear behaviour of the modified specimens out of 1.2367 is comparable to the alloyed and coated surfaces of the substrate material WP7V. While the surface wear can be decreased by 25 % for the alloyed tools with 1.3348, the adhesive wear is reduced for the coated pin with AlCrN by 50 % and for AlCrTiN by 70 %. According to these results the usage of the adapted surfaces for the hot stamping process could be verified.

Friction behaviour

Beside the wear characterization, an analysis of the tribological behaviour was also carried out. The determined friction coefficients in the hot strip drawing test are depicted in Fig. 6.

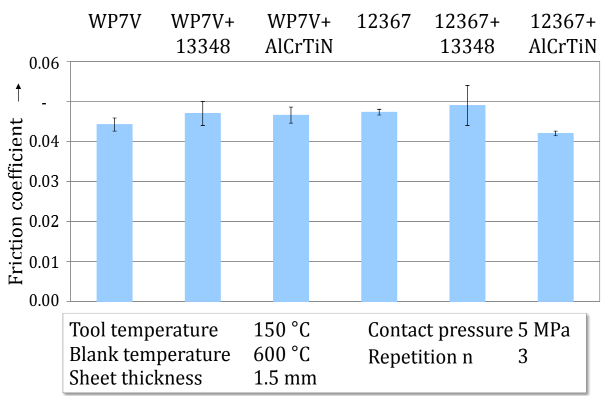
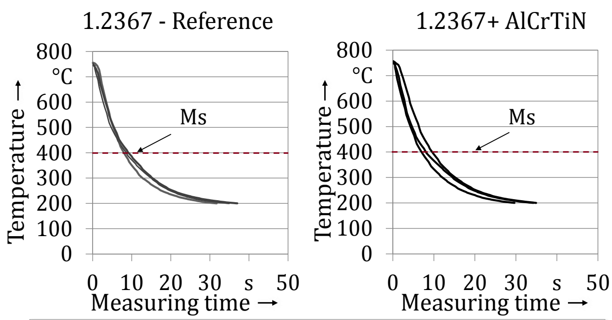


Fig. 6. Friction behaviour for modified tool surfaces.

For all the materials, similar friction values between 0.42 till 0.49 can be achieved. It can be assumed, that for the chosen process parameters no significant damage of the AlSi coating occurs during the experiments. Schwingenschlögl et al. [25] confirmed in their study, that the sliding speed, contact pressure and temperature have a great influence on the friction behaviour. In case of an increased thermal load between tool and workpiece, the AlSi coating of the blank will be damaged, which results in a higher adhesive wear on the tool surface. During sliding the local temperature distribution in the contact zone between friction jaw and the blank have a great influence on the friction and wear behaviour. In case of lower sliding speeds, the temperature between tool and the blank is increasing, which results in a heating of the jaw surface and favours the formation of layer build-up on the tool surface resulting in adhesive wear. Considering the chosen process parameters, comparable friction properties are achieved and an application from the tribological point of view is possible for the selected surface modifications.

Quenching

In order to ensure that a coating system of the tools does not influence the thermal conditions of hot stamping process, quenching test were performed. After austenitization, the samples out of 22MnB5 were positioned on three spring seated pins to prevent rapid cooling of the surfaces before the contact pressure was applied. The investigations were carried out at 150 °C tool temperature and 10 MPa contact pressure. For the first test series two uncoated cooling plates were used. In the next experiments they were replaced by two coated tools.



Contact pressure	10 MPa	Repetition n:	3
Austenitization temperature	930 °C	Tool Temperature	150 °C
Sheet thickness	1.5 mm		

Fig. 7. Cooling temperature during quenching test.

The measured temperature profiles in Fig. 7 were used to identify the cooling rate for coated surfaces with a layer thickness of 2 µm.

During quenching the thermocouples record the temperature curves, which show for both experiments a comparable cooling behaviour. After positioning the blank on the three pins of the cooling plates, the starting temperature is 750 °C. The quenched specimens are cooled down at 200 °C, which is identical to the hot stamping process after forming. According to the time temperature transformation (TTT) a high cooling rate influence the transformation of austenite into martensite, bainite or pearlite and ferrite [26]. In order to start the martensite transformation and to avoid bainite a high cooling rate is necessary. For the steel grade 22MnB5 the temperature Ms at which the martensitic transformation begins is commonly at 400 °C, which is achieved after approximately 10 s. The cooling rate is determined with $T_1 = 750$ °C (1023.15 K) and T_2 = 400 °C (673.15 K) by the formula:

$$\boldsymbol{q} = \frac{\boldsymbol{T_1 - T_2}}{\boldsymbol{\Delta t}} \tag{1}$$

The measuring time Δt is between 8 and 12 s. For the coated surfaces with AlCrTiN and the uncoated 1.2367 the calculated value is between 29 K/s and 35 K/s. A minimum cooling rate of 27 K/s [26] is required for a fully phase transformation into martensite. Since the results of the experiments are higher, this requirement was realized. In addition, an influence of the coating system on the thermal behaviour was not verified. For this reason an application of the AlCrTiN coating for hot stamping operations is possible.

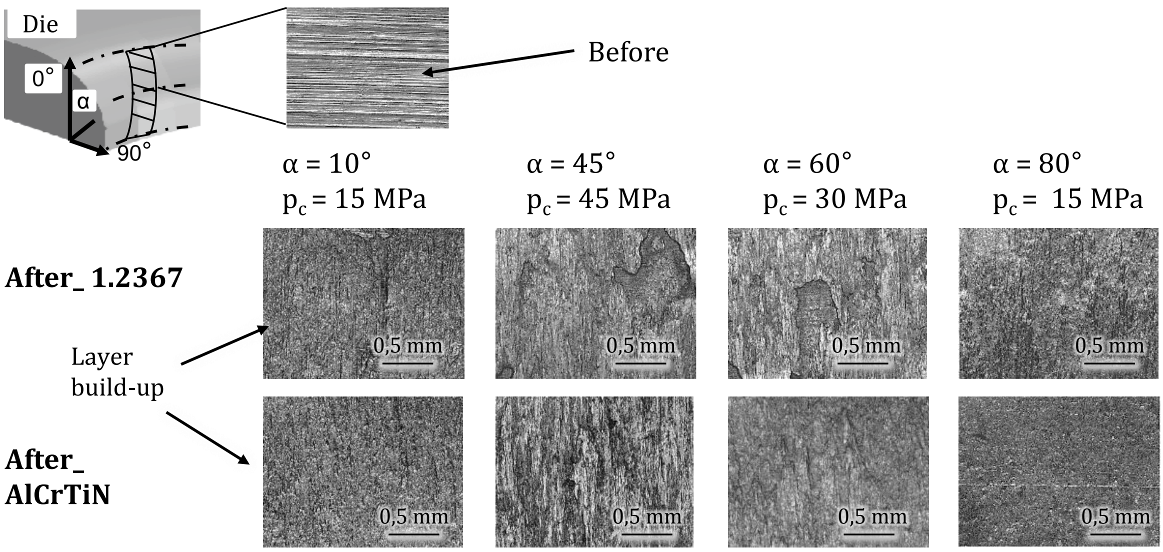
Deep drawing

In this study the results regarding the wear characterization were validated in cup deep drawing tests. The main purpose of this analysis is to verify whether a transferability of the surface modification to model geometries can be ensured. A verification of the influence of coated surfaces on the tool life is also performed by the examination of the different wear behaviour of unmodified and modified tools. In contrast to the wear examination with the modified pin-on-disc test, deep drawing operations cause a locally higher mechanically load along the die surface. The wear behaviour is considerably influenced by these stresses, resulting in a locally different amount of surface wear. For this reason, an application of a wear protective layer for hot stamping tools only for high stressed areas should be considered. In addition, a local surface modification would guarantee a high level of economic efficiency, since a complex rework of the entire forming tool is not necessary and segmented tools can also be used.

Unlike conventional methods a numerical model was created to determine the surface pressure distribution along the die radius. The simulation was carried out for round cup geometry and was validated using experimentally measured force-displacement curves and temperature distribution of the cup.

After 200 strokes the surface along the die radius were measured with a laser-scanning microscope. The determined surface roughness was compared with the measured values before the experiment in order to identify the areas with the highest adhesive layer build-up. The surface topographies, the roughness values and the calculated distribution of the contact pressure were used to evaluate the wear behaviour under consideration of the high stressed areas. The experimental and numerical results are shown in Fig. 8 for an uncoated 1.2367 and a coated die with AlCrTiN.

The tool topographies indicate that the highest layer build-up occurs on the unmodified die. In addition to the adhesive wear, material has broken out of the tool surface. This wear mechanism is caused by adhesive and abrasive processes. During sliding, former material adhesion is separated from the tool surface due to the locally metallic bonds between die and blank. The most wear critical areas can be located at α=45° and α=60° of the die radius by comparing the topography images and the calculated contact pressure from the simulation. The maximum mechanically loads of 45 MPa and 30 MPa also occur in these zones. Due to the high contact pressure, a larger true contact area between tool and blank is formed. As a result the binding forces and therefore the adhesive wear and also the abrasive wear increases. For the coated die no abrasively removed areas were detected. Even at the highest stressed area only minor adhesive wear was determined and only a slight amount of material is broken out of the surface. By using a coating system it is possible to reduce the surface damage. The material transfer of the aluminium-silicon particles adhere on the die surface and change the contact conditions between the die and the blank. Since the highest amount of layer build-up occur at approximately α= 45 ° along the die radius, the contact between the surfaces decreases at the run-out area at approximately α=60° till 80 °.



Strokes	200	Lens:	20 x
Forming speed:	50 mm/s	Forming Press:	Lasco TP100
Austenitization temperature:	930 °C	Microscope:	Keyence VK-X2000

Fig. 8. Tool topographies for modified and unmodified tool surfaces compared to the determined contact pressure distribution of the numerical simulation.

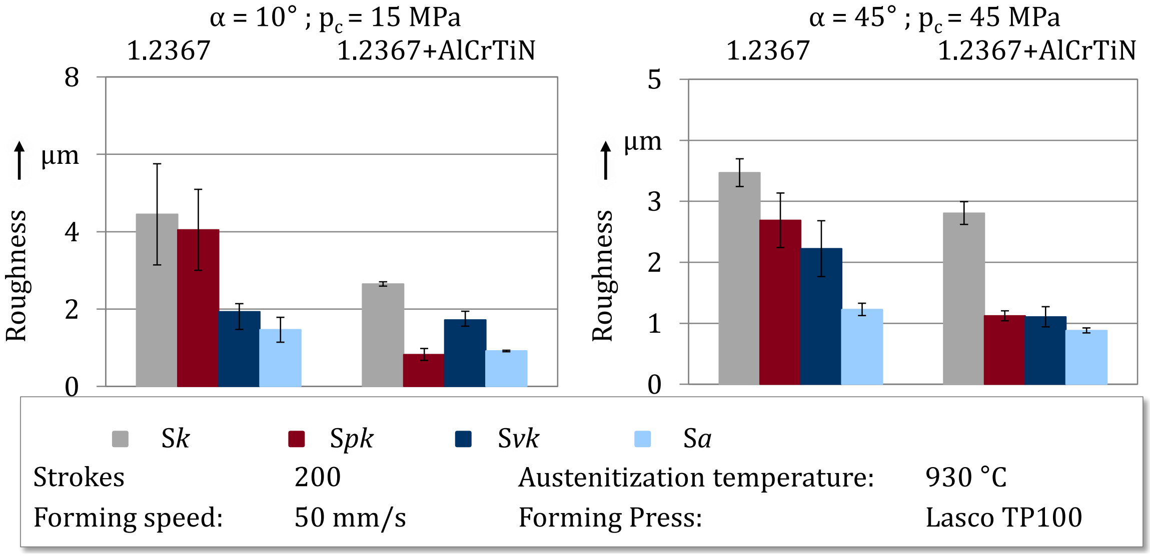


Fig. 9. Surface roughness on wear critical tool areas for uncoated and coated tools.

In order to confirm this assumption the surface roughness for the different stressed areas was examined. The wear resistance of the different materials was analysed by the arithmetic mean roughness *Sa*, the core depth *Sk*, reduced peak height *Spk* and reduced depth of the groove *Svk*. These parameters are suitable for this evaluation, because *Sa* is direction-independent and therefore not influenced by a preferential direction while the other values characterize the material proportion over the height. The measured roughness values are shown for the worn area at 10° and 45° of the die radius in Fig. 9. For one die three different zones of the tool were examined and the average value of each roughness parameter was calculated.

The main increase of the surface roughness was detected at α= 45 ° where the highest load with 45 MPa occurs during the forming operation. The results of the tool topography could also be confirmed. While the uncoated tools show severe surface wear, the coating system AlCrTiN reduces the sign of wear. In addition, the standard deviation for the measured roughness of the substrate material 1.2367 is higher than for the values of the coated surfaces. Since a larger amount of material breaks out of the unmodified die surfaces, the roughness variation increases.

5. CONCLUSION

The hot stamping process is commonly used in order to manufacture ultra-high strength steels. Due to the high temperature, which occur during the forming operation, the tools are highly thermo-mechanically stressed resulting in an increased surface wear. In this regard, the adhesive wear is dominant in direct hot stamping. In order to ensure a consistent part quality, a time and cost consuming of the tools is required. For this reason, a suitable wear protection is required to increase the wear resistance and the tool life. Within the scope of this work, the thermal and tribological behaviour of different alloyed and coated tool surfaces was investigated. In the first experiments, the wear and friction behaviour was evaluated. For the analysis a new developed algorithm was used to calculate the wear volumes. In this regard, the alloyed substrate material with nickel content did not decrease the surface wear. Since nickel is susceptible to adhesive wear, the experiments showed a severe adhesion of AlSi particles to the tool surface. By using filler wire materials made of chromium, molybdenum and carbon or with titanium content the highest wear resistance after the modification could be achieved. Compared to the laser alloying process, the wear resistance could be further increased by coating the surfaces. For the experiments coating systems of AlCrN and AlCrTiN were investigated. By adding titanium, a significant reduction in adhesion wear could be achieved. Since titanium consists of a low density of moving electrons, the bonding forces between tool and blank can be decrease. For this reason, the modified tool surfaces are less prone to metallic adhesion. The friction behaviour was also studied for all the samples and compared to each other. It could be verified that the friction behaviour is similar to the industrial process. In addition to the tribological analyses, the thermal conditions were investigated. A suitable wear protection for hot stamping tools has also to ensure a high cooling rate after modifying the tools. In quenching tests the determined values are between 29 K/s and 35 K/s, which are above the required minimum of 27 K/s. According to these results an influence of the coating system on the thermal behaviour was not identified. In the last step, the surface modification was applied on a die to validate in cup deep drawing tests if an application for hot stamping tools is possible. In addition, the contact pressure along the die radius was numerically analysed. After 200 strokes the contact area of the tool was measured with a laser scanning microscope and the surface roughness was determined. The experimental results were compared to the calculated contact pressure distribution. The adhesive wear increases at 45° of the die radius, at which the highest surface pressure occurs. Due to the surface modification a significant decrease of the surface wear was possible.

REFERENCES

[1] M. Naderi, *Hot Stamping of Ultra High Strength Steels*, PhD thesis, RWTH Aachen, Germany, 2007.

[2] S. Bruschi, A. Ghiotti, *Hot stamping*, in Materials Science and Materials Engineering, from Comprehensive Materials Processing, vol. 3, Padova, Elsevier, pp. 27-54, 2015.

[3] H. Karbasian, A.E. Tekkaya, *A review on hot stamping*, Journal of Materials Processing Technology, vol. 210, iss. 15, pp. 2103-2118, 2010, doi: 10.1016/j.jmatprotec.2010.07.019

[4] A. Ghiotti, S. Bruschi, F. Medea, A. Hamasaiid, *Tribological behavior of high thermal conductivity steels for hot stamping tools*, Tribology International, vol. 97, pp. 412-422, 2016, doi: 10.1016/j.triboint.2016.01.024

[5] J. Hardell, S. Hernandez, S. Mozgovoy, L. Pelcastre, C. Courbon, B. Prakash, *Effect of oxide layers and near surface transformations on friction and wear during tool steel and boron steel interaction at high temperatures*, Wear, vol. 330-331, pp. 223-229, 2015, doi: 10.1016/j.wear.2015.02.040

[6] A. Yanagida, A. Azushima, *Evaluation of coefficients of friction in hot stamping by hot flat drawing test*, CIRP Annals, vol. 58, iss. 1, pp. 247-250, 2009, doi: 10.1016/j.cirp.2009.03.091

[7] A. Ghiotti, S. Bruschi, F. Medea, *Comparison of tribological and wear performance of AlSi and Zn coatings in hot stamping of boron steel sheets*, Wear, vol. 332-333, pp. 810-821, 2015, doi: 10.1016/j.wear.2015.01.046

[8] T. Schrader, *Grundlegende Untersuchungen zur Veschleißcharakterisierung beschichteter Kaltmassivumforwerkzeuge*, PhD thesis, Department of Mechanical Engineering, Friedrich-Alexander-University of Erlangen Nuremberg, Germany, 2016.

[9] E. Doege, B.-A. Behrens, *Warmarbeitsstähle für den Gesenkbau*, In: Handbuch Umformtechnik, Springer Verlag, pp. 615-620, 2007.

[10] Ch. Escher, J. Wilzer, *Tool steels for hot stamping of high strength automotive body parts*, 3rd International Conference on Stone and Concrete Machining (ICSCM), Ruhr-Universität Bochum Conference proceedings, pp. 219-228, 2015, doi: 10.13154/icscm.3.2015.219-228

[11] K. Hofmann, F. Neubauer, M. Holzer, V. Mann, F. Hugger, S. Roth, M. Schmidt, *Effect of laser beam alloying strategies on the metallurgical and mechanical properties of hot forming tool steels*, Physics Procedia, vol. 83, pp. 264-276, 2016, doi: 10.1016/j.phpro.2016.08.023

[12] H. Czichos, K.-H. Habig, Adhäsion, In: Tribologie Handbuch (Ed: 3), Vieweg Teubner, pp. 86-92, 2010.

[13] Datasheet WP7V and 1.2367 from Dörrenberg.

[14] Datasheets AX-Mo, AX-NiMoCr90, AX-308L, AX-316L, AX-312, AX-SGZink/SG2-Ti and 1.3348 from Alunox welding alloys group.

[15] T.S. Kumar, S.B. Prabu, G. Manivasagam, K.A. Pad, *Comparison of TiAlN, AlCrN, and AlCrN/TiAlN coatings for cutting-tool applications*, International Journal of Minerals, Metallurgy and Materials, vol. 21, iss. 8, pp. 796-805, 2014, doi: 10.1007/s12613-014-0973-y

[16] D.W. Fan, B.C. De Cooman, *State-of-the-Knowledge on Coating Systems for Hot Stamped Parts*, Steel research international, vol. 83, iss. 5, pp. 412-433, 2012, doi: 10.1002/srin.201100292

[17] M. Windmann, A. Röttger, W. Theisen, *Formation of intermetallic phases in Al-coated hot-stamped 22MnB5 sheets in terms of coating thickness and Si content,* Surface & Coatings Technology, vol. 246, pp. 17-25, 2014, doi: 10.1016/j.surfcoat.2014.02.056

[18] E. Hornbogen, H. Warlimont, *Korrosionsschutz*, In: Metalle, Struktur und Eigenschaften der Metalle und Legierungen, vol. 6, Springer Verlag, pp. 346-348, 2016.

[19] P. Sahoo, S. K. Das, *Tribology of electroless nickel coatings – A review,* Materials and Design, vol. 32, iss. 4, pp. 1760-1775, 2011, doi: 10.1016/j.matdes.2010.11.013

[20] J.M. Fildes, S.J. Meyers, C.P. Mulligan, R. Kilaparti, *Evaluation of the wear and abrasion resistance of hard coatings by ball-on-three disk test methods- A case study*, Wear, vol. 302, iss. 1-2, pp. 1040-1049, 2013, doi: 10.1016/j.wear.2012.11.018

[21] G.A. Fontalvo, R. Humer, C. Mitterer, K. Sammt, I. Schemmel, *Microstructural aspects determining the adhesive wear of tool steels*, Wear, vol. 260, iss. 9-10, pp. 1028-1034, 2006, doi: 10.1016/j.wear.2005.07.001

[22] K. Bobzin, *Review High-performance coatings for cutting tools*, CIRP Journal of Manufacturing Science and Technology, vol. 18, pp. 1-9, 2017, doi: 10.1016/j.cirpj.2016.11.004

[23] J.M. Wheeler, R. Raghavan, V. Chawla, M. Morstein, H. Michler, *Deformation of hard coatings at elevated temperature*, Surface & Coatings Technology, vol. 254, pp. 382-387, 2014, doi: 10.1016/j.surfcoat.2014.06.048

[24] M. Çöl, D. Kir, E. Erişir, *Wear and blanking performance of AlCrN PVD-coated punches*, Material Science, vol. 48, iss. 4, pp. 514-520, 2013, doi: 10.1007/s11003-013-9532-3

[25] P. Schwingenschlögl, M. Weldi, M. Merklein, *Investigation of the influence of process parameters on adhesive wear under hot stamping conditions*, 36th IDDRG Conference – Material Modelling and Testing for Sheet Metal Forming, Journal of Physics, Conference Series 896, pp. 1-8, 2017, doi: 10.1088/1742-6596/896/1/012048

[26] M. Merklein, J. Lechler, *Investigation of the thermo-mechanical properties of hot stamping steels*, Journal of Materials Processing Technology, vol. 177, iss. 1-3, pp. 452-555, 2006, doi: 10.1016/j.jmatprotec.2006.03.233