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The Analysis of Complex Tribological System of Single Point Incremental Sheet Metal Forming - SPIF

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In contemporary industrial production the ecological aspects have increasingly important role in selection of sheet metal forming process. To produce sheet metal parts with minimum environmental burdening the shortening of forming processes including the procedures for production of appurtenant forming tools as well as decrease use of lubricant is prerequisite. In general, majority of the sheet metal forming processes demand use of lubricants with oils involving additives, which are hazardous for several reasons. Therefore, the paper is focused towards the analysis of different manners of lubrication (dry contact, liquid lubricant and hard coatings) and to investigate tribological properties during a single point incremental forming (SPIF) technology, which is nowadays very attractive and manly used for small and medium batch production. The first phase of the evaluation was performed on a model test rig by simulating single point incremental forming process, where the coefficient of friction was recorded and compared as a function of lubrication method used. In addition, the paper presents the forming tool temperature measurements for three different manners of lubrication, arising from friction during the single point incremental forming of the pyramid-shaped part.

Keywords: incremental sheet metal forming, friction, DLC coatings

0 INTRODUCTION

The modern industrial praxis is oriented towards the environmental friendly production consisting of low lubricant use, optimum set-up of forming operations as well as development of new innovative forming processes. One of the most attractive forming processes at the moment applied for small batch production and prototype production of very complex components and parts is single point incremental sheet metal forming. The technology is very flexible, has ability to quickly response to part geometry modifications with minimum expense and on the other hand requires essential longer forming time per part in comparison to conventional forming processes, like deep drawing, bulging, etc. [1] and [2]. Some products performed with SPIF are presented in Figure 1. However, majority sheet metal forming operations require by more pretending forming operations the use of lubricants involving additives, like phosphorus, sulphur, zinc, etc., which are unsafe for several reasons. In order to avoid any unsafe influences the special airing systems, electrostatic filters and protective clothes are needed. Beside all, the intensive application of lubricants and use of inappropriate ones demand cleaning of the workpieces after forming and before their assembly into the final product or before additional procedures of surface treatment (colouring, galvanizing, welding, etc.). Generally, the cleaning costs may reach up to 10 % of product price [3].

All above mentioned are the reasons why the liquid lubricants in forming operations have to be minimized or even replaced with thin hard

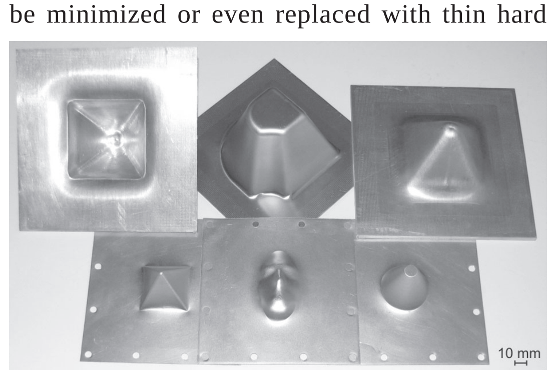

Fig. 1. *Products performed with SPIF*

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coatings. In the production companies the hard coatings (like TiN, TiCN, TiAlN, CrN, etc.) are frequently used at least twenty years to protect and enhance the lifetimes of tools by dry machining in metal cutting applications. In contrast to cutting tools, the majority of forming tools is still uncoated. This is due to the large size and complex shape of most conventional forming tools, which makes it difficult to apply a coating and to obtain good adhesion between the coating and the substrate material [4]. Furthermore, in the case that coating fails on the forming tool because of poor adhesion, coating fragments could become a source of abrasive particles within the system. This could lead to poor surface quality of the product and even to the destruction of a very expensive tool. There are also many other reasons why the hard coatings are not frequently used in forming applications. One of the most important is the relatively high coefficient of friction generated by most of the commercial ceramic coatings [5], which leads to a high temperature between the tool and the workpiece and consequently to a sticking of the formed material on the forming tool surface. However, in recent years remarkable progress has been done in the field of hard coatings deposition as well as on the development of coatings on the basis of hard carbon (e.g. diamond like carbon - DLC). These coatings with the major portion of the graphite bonds have in contrast to conventional bonds excellent frictional properties whereat they are still very hard. Because of low friction coefficient and high hardness the DLC coatings could be one of the most appropriate for the movable machine parts protection and also for the forming operations, especially for the incremental forming where only small hemispherical tool head has to be coated.

However, the aim of this research was to investigate the possibilities of using hard coatings on the forming tool by single point incremental forming technology from the frictional properties and temperature between the workpiece and forming tool point of view.

1 SPIF – PROCES DESCRIPTION

Single point incremental forming, also known as dieless forming, is nowadays well known sheet metal forming method. The sheet metal could be formed to a complicated shape without a dedicated die (Fig. 2).

The rod-shaped forming tool with a smooth hemispherical head is clamped into the spindle of the forming machine. The forming tool is usually made of hard material like cemented carbide. The sheet metal is positioned and clamped with the upper blank holder. It is pressed towards the lower blank holder in which the simple die is placed. The whole support tool is inserted and fixed on the worktable of the forming machine. While the forming tool presses and locally deforms the workpiece directly under the tool head with a very small value of deformation, the blank holder and die remained fixed during the entire forming process. As the forming tool follows the predetermined tool path and gradually forms the workpiece in a series of incremental steps until it reaches the final depth it is also spinning at a certain number of revolutions per minute. The steps and process parameters of single point incremental sheet metal forming are shown in Figure 2.

2 DEPOSITION OF THE USED COATINGS

In this investigation three different coatings (CrN, DLC and TiAlN + DLC) were used. The coatings were prepared by different PVD procedures at JOANNEUM RESEARCH, Leoben Laser Centre and Institute “Jozef Stefan” in Ljubljana, respectively. The investigated coatings were deposited on a hemispherical tool head made from cemented carbide and/or ball bearing steel (100Cr6). Before deposition the coatings were grounded and sputter-cleaned in order to obtain optimum adhesion between coating and substrate. The CrN coating was deposited in a Balzers BAI 730 thermionic arc ion plating apparatus. DC ion etching was performed using Ar ions. During deposition Cr targets were evaporated by electrons

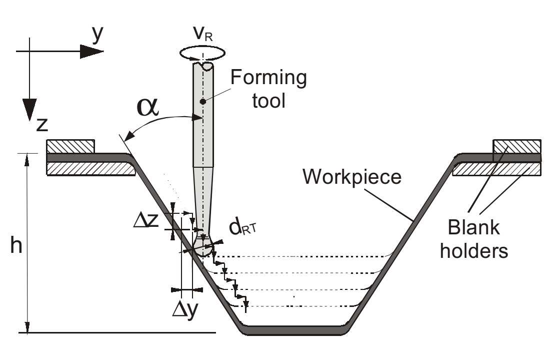

Fig. 2. *Principles and steps of SPIF*

using Ar as the working gas, while N_2 was used as the reactive gas. Other deposition parameters are: base pressure below 2 mPa, working gas pressure 200 mPa, deposition temperature 450 °C and film thickness 3 µm. The CrN coating was chosen for its antiadhesive properties.

The DLC coatings were prepared in a semiindustrial apparatus. The ion etching was performed by the anode layer source using Ar ions. The films were deposited by pulsed laser deposition using four Nd:YAG lasers ablating the carbon targets. As source for hydrogen and nitrogen, C_2H_2 and N_2 were used, respectively. The deposition temperature was below 100 °C. The film thickness was around 1 µm. For this purpose a multilayer coating was deposited, which was achieved by introducing the reactive gases. The structure was a-C / a-C:N. In this case the individual layers have a different ratio of sp3 bonds, hardness and toughness. In this way the multilayer structure was high sp3/ low sp3/ high sp3/ low sp3 etc.

In order to obtain optimum adhesion a composite coating (a hard base coating - TiAlN and a relatively soft topcoat – multilayer DLC) was prepared. However, prior to the DLC coating deposition a TiAlN intermediate layer was deposited. The TiAlN coating was deposited by sputtering in a commercial CemeCon CC 800 apparatus, which is equipped by four unbalanced magnetron sources, while the substrates are mounted on planetary holders. Ion etching is performed in RF mode using Ar ions. For deposition, N_2 is used as reactive gas and a mixture of Ar+Kr as working gas, yielding a film thickness of about 3 µm. The working pressure was around 700 mPa, while the base pressure was below 2 mPa. The deposition temperature is around 450 °C. The TiAlN coating was chosen as being a proven protective coating with high hardness (3500 HV).

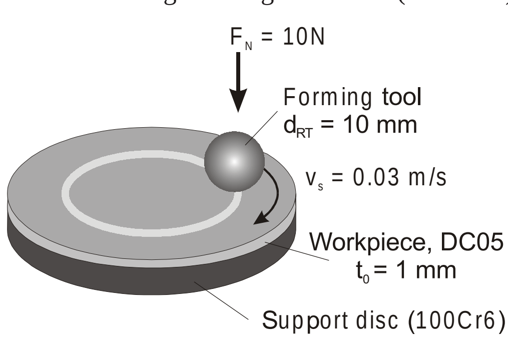

Fig. 3. *Pin-on-disc test*

After TiAlN intermediate layer the DLC coating was deposited in the same way described in previous paragraph.

3 EXPERIMENTAL WORK AND RESULTS

3.1 Tribological Test

Since the friction coefficient can not be measured during single point incremental forming the tribological tests were performed on a pin-on-disc test machine, which presents in the initial testing stage the most reliable method to describe the actual conditions during SPIF. It is worth pointing out that in case of pin-on-disc test the tool contacts the workpiece over the same rounded loop repeatedly whereas in case of SPIF the forming tool never exactly touches the same workpiece area.

However, tribological tests were carried out under dry and oil lubricated sliding conditions. The upper specimens were the forming tools with the diameter of 10 mm made of cemented carbide and coated 10 mm bearing steel balls, respectively. Bearing steel balls (100Cr6) were included in the investigation in order to investigate the possibility of replacing cemented carbide with cheaper substrate. Coated and uncoated forming tools were loaded against rotating 1 mm thick steel sheet plates made from cold-rolled DC05 steel mounted on a hardened 100Cr6 discs, used as a load support (Fig. 3). The normal load applied was 10 N, which corresponds to a maximum Hertzian contact pressure of 1 GPa and sliding speed set to 0.03 m/s. Sixty minute tests corresponding to a total sliding distance of ~100 m were performed at a relative humidity of 50% and a room temperature of 20°C. Oil lubricated tests for uncoated cemented carbide forming tools serving as a reference point were performed with a standard forming oil SYLAC80-05, which does not contain chlorine and steel plate being submerged in lubricant. Prior to testing all test samples were ultrasonically cleaned in ethanol.

During testing coefficient of friction was monitored continuously as a function of time, while contact surfaces were analyzed after the test by means of Optical Microscopy (OM) and Scanning Electron Microscopy (SEM).

Figure 4 shows coefficient of friction curves for different coatings tested on Pin-Disc machine against DC05 steel plates. In the case of cemented carbide forming tool - pin, which was used as a

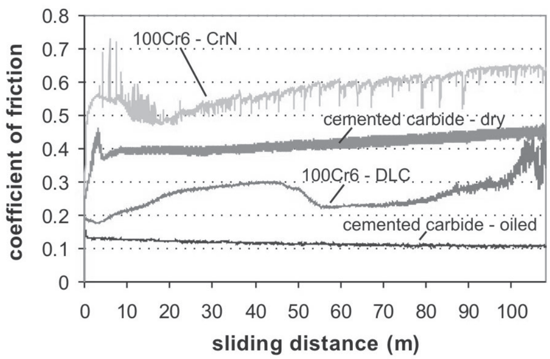

Fig. 4. *Coefficient of friction curves for cemented carbide forming tools and 100Cr6 coated balls*

reference material, coefficient of friction reached steady-state values of about 0.1 if running with forming oil and between 0.4 and 0.45 when running dry (Fig. 4). Relatively high friction under dry sliding conditions indicates adhesion of DC05 steel to the cemented carbide forming tool surface.

CrN coating deposited on bearing steel ball and tested dry showed even higher initial friction of over 0.5, which dropped during first 20 m of sliding as contact surfaces accommodate to each other and smoothening takes place. However, as sliding proceeds coefficient of friction starts to increase and after 100 m of sliding reaches values of about 0.65. Steady friction increase and its abruptions indicate adhesion of DC05 steel to the CrN surface (Fig. 5), followed by adhered material removal. As sliding proceeds contact temperature will increase, thus intensifying the process of DC05 steel adhesion and friction increase (Fig. 4).

On the other hand, DLC coating deposited on the 100Cr6 balls showed low initial friction against DC05 steel even under dry sliding conditions, with the coefficient of friction being in the range of 0.15 to 0.18. As shown in Figure 6 no adhesion of the DC05 steel could be detected in the early stages of sliding. However, as sliding proceeds DLC coating gets removed, either by spallation or wear causing adhesion of DC05 steel to the steel substrate (Fig. 6) and friction increase (Fig. 4).

When deposited on cemented carbide forming tools DLC coatings showed immediate failure, as indicated by high friction recorded at the very beginning of sliding (Fig. 7), and

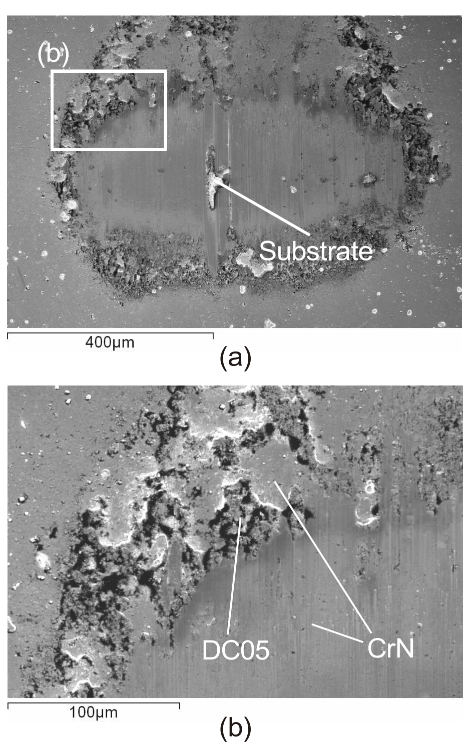

Fig. 5. *SEM micrograph of CrN coated ball tested against DC05 steel after 100m of sliding*

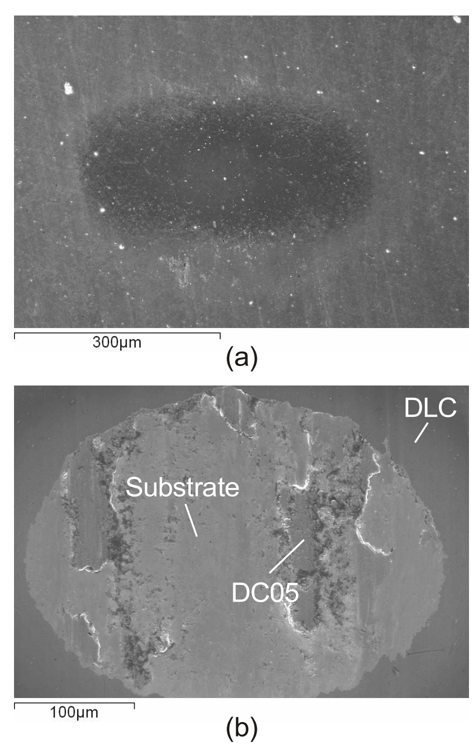

Fig. 6. *SEM micrographs of DLC coated 100Cr6 ball tested against DC05 steel after (a) 10 m of sliding and (b) 100 m of sliding*

confirmed by surface analysis. Further sliding showed similar friction as recorded for uncoated cemented carbide forming tools, indicating adhesion or transfer of DC05 steel material to the cemented carbide substrate. Surface analysis confirmed DLC coating spallation, which is probably caused by unsuitable coating adhesion to the cemented carbide substrate, followed by transfer of steel sheet material to the cemented carbide substrate.

Use of TiAlN support layer considerably improved tribological behaviour of DLC coating when deposited on cemented carbide forming tools, with the DLC coating preventing DC05 steel material transfer for about 20 m of sliding (Fig. 7). However, even with the TiAlN support layer DLC coating eventually failed, leading to cemented carbide/steel contact conditions and material transfer, as shown in Figure 8.

3.2 The Temperature Measurements

The increase of the forming tool temperature usually has a positive influence on the formability but sometimes when the temperature is too high it could cause the sticking of the workpiece material on the forming tool, what leads to the fracture of the workpiece. Beside this, high temperature could also have negative influence on some hard tool coatings. For example, in the case of the tools coated with DLC coating high temperature causes coating spallation because of its poor thermal stability, which beside high internal stresses is one of the greatest weaknesses of the DLC coatings. All above mentioned is the reason why the temperature between the forming tool and workpiece material play so important role in order to assure perfection of the single point incremental formed parts.

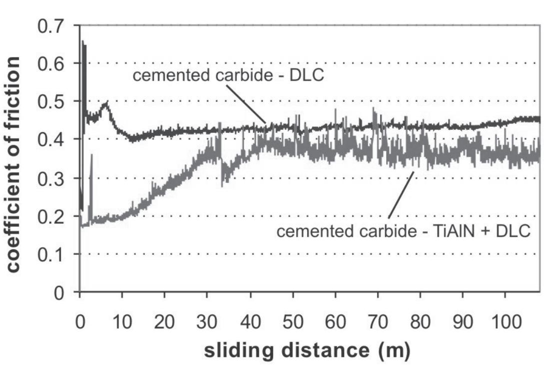

Fig. 7. *Coefficient of friction curves for DLC coatings when deposited on cemented carbide pins*

In order to define real forming tool temperature arising from friction between forming tool and workpiece during SPIF the production of pyramid-shaped part was used as a case study (Fig. 9).

The SPIF experiments were carried out on the CNC milling machine Mori Seiki with the FANUC MSC-521 control system. Due to its frequent use in sheet metal forming production, the same material (DC05) selected for tribological tests was used. Material properties for cold-rolled DC05 steel were obtained by a uniaxial tensile test and are shown in Table 1.

Table 2 shows the selected process parameters for SPIF, which are based on preliminary tests [6].

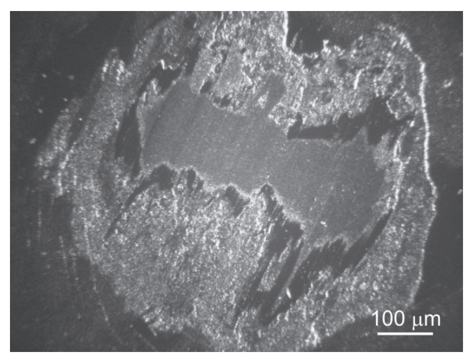

Fig. 8. *OM micrograph of TiAlN+DLC coated cemented carbide forming tool after 100 m of sliding against DC05 steel*

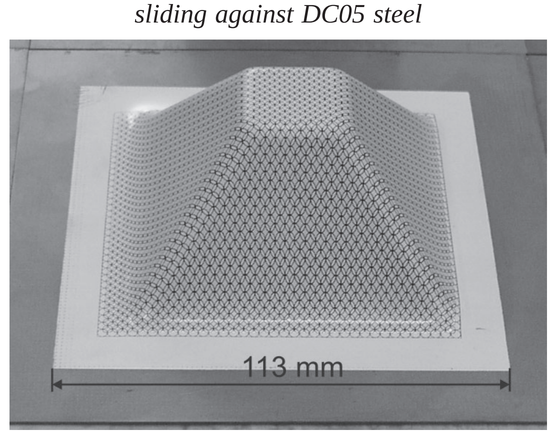

Fig. 9. *Pyramid-shaped part used as a case study and its approximate dimension*

Table 1. *Material properties of DC05 steel*

C = 531.5	strength coefficient [MPa]
n = 0.23	strain hardening exponent
r_0 = 1.59	material anisotropy
r_{45} = 1.06	
r_{90} = 1.76	
E = 210	Young's modulus of elasticity [GPa]
ρ = 7850	density [kg/m^3]
ν = 0.3	Poisson's ratio
t_0 = 1	initial specimen thickness [mm]

Table 2. *Applied SPIF process parameters*

Wall angle α	60°
Forming depth h	38 mm
Rotation speed v_R	60 r.p.m.
Punch diameter d_{RT}	10 mm
Tool path	by steps - CCW
Feed rate f	1700 mm/min
Vertical step size Δz	0.5 mm
Lubricant	SYLAC80-05

The contact temperature was measured on the forming tool for three different contact conditions: liquid lubricant, dry contact and hard coating, respectively. The results of the contact temperature were obtained using special IR thermography camera ThermaCAM^{TM} S60 with the accuracy of ± 2°C [7].

In the first case the workpiece surface was oiled and the contact temperature was measured at the end of the uncoated cemented carbide forming tool rotating in natural direction (NTR). The results in (Fig. 10) show slight increase of the temperature during whole forming process. At the end of the process the maximum temperature of 48.7°C could be observed. In case of additional forming procedure the essential increase of tool temperature could not be expected because of the oil presence.

In the second case TiAlN+DLC coated cemented carbide forming tools rotating in natural direction was analyzed. The TiAlN+DLC coating was selected because it shows the best results by tribological tests. However, the temperature measurement results of such coating system shows similar trend of the temperature curve like the curve obtained by liquid lubrication system, whereas the former lies a little higher (Fig. 10). The reasons could be found in higher friction coefficient (Fig. 7), the absence of cooling/oiling system and very unsuitable coating adhesion and coating spallation in the contact zone during SPIF as presented in Figure 11. Similar results were obtained also by the tribological test (Fig. 8).

When dry contact is taken into account two various tests involving different cemented carbide forming tool rotation strategy were analyzed. Two reasons for concern over the tool rotation strategy, relative to the tool motion, are the heating that occurs and consequentially the quality of the SPIF formed product [6]. The most obvious origin of heating due to the tool rotation strategy are sliding and rolling friction. As the tool travels over the workpiece surface it could rotates in natural or unnatural directions relative to the tool motion. In the case of natural tool rotation (NTR) with the optimum rotation speed relative to the feed rate according to preliminary tests [6] the tool rolls over the workpiece surface during whole forming process. Therefore, excessive heating could not be observed. The results of the thermography analysis during whole SPIF process is evident from the diagram in the Figure 10, whereas the temperature distribution of dry contact between the cemented carbide forming tool and workpiece rotating in NTR after the forming time of 6 min presents Figure 12.

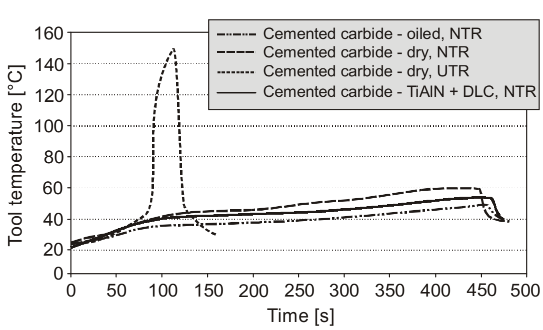

Fig. 10. *The tool temperature in dependence of time during SPIF by various lubrication methods*

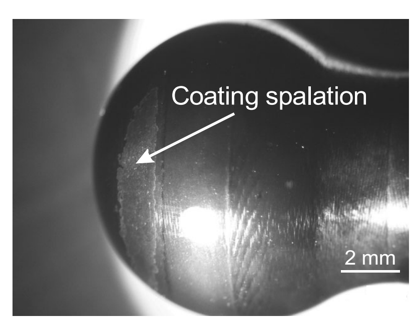

Fig. 11. *OM micrograph of TiAlN+DLC coated cemented carbide forming tool already after first SPIF formed part*

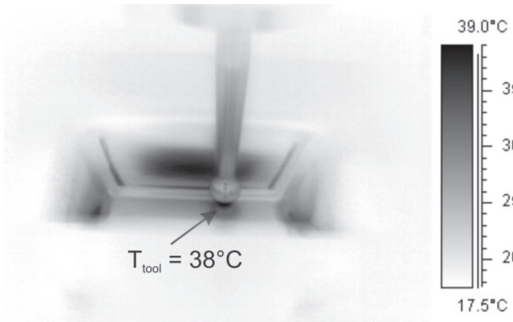

Fig. 12. *The temperature distribution of dry contact, NTR, forming time 382s*

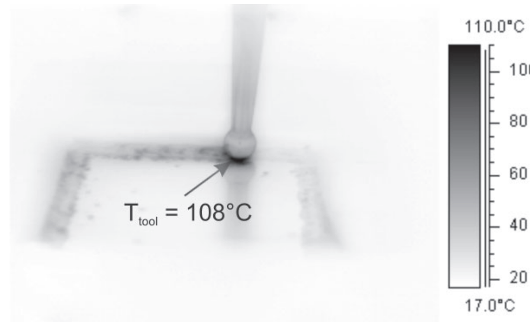

Fig. 14. *The temperature distribution of dry contact, UTR, forming time 117s*

In contrast to NTR the forming tool in the case of unnatural tool rotation (UTR) slides along the workpiece surface, kneading the base material (Fig. 13b), whereat extreme heating due to the large value of sliding friction could be observed. After a few number of revolutions the temperature reaches an extremely higher value (T_{max} = 150°C) than in the other three cases (Fig. 10). Beside this, the sticking of the workpiece material on the forming tool appears (Fig. 13b), while in the case of NTR no base material sticking and excellent surface quality could be observed (Fig.13a).

The temperature distribution of dry contact condition using UTR after the forming time of 117 secs. presents Figure 14.

4 CONCLUSIONS

In the case of incremental sheet metal forming with a hemispherical rigid tool the coating ability to prevent the adhesion of the workpiece is as important as its wear resistance, because of the long forming tool path in order to achieved final product. Usually, the coatings with high wear resistance have besides high friction coefficient also high tendency to sticking of formed material what does not represent the best solution for improving tool lubrication properties by SPIF. Furthermore, the poor adhesion of the coating may lead to the coating crumbling and consequently to the forming tool damaging. On the other hand the coatings with low friction coefficient and anti sticking condition do not reach high wear resistance.

However, from the investigation could be concluded, that CrN coating shows good load-carrying capacity when tested against DC05 steel, while high friction and high tendency for the DC05 steel to adhere to CrN surface does not make CrN coating a good candidate for dry forming of used steel. On the other hand, DLC coating shows low friction against DC05 steel even under dry sliding conditions, but adhesion is relatively poor. Using multilayer DLC coating with TiAlN support layer the adhesion and the tribological properties of DLC coating can be improved, but the adhesion is still not good enough because of long forming tool path in order to achieved final product. Furthermore, the thermography analyses shows that the low temperature appeared by the hard coating system does not have influence on the adhesion of the DLC coating. It has been found that is the tool temperature directly connected with the friction condition for particular SPIF parameters used. The increase in the tool temperature appears with the increase in the friction coefficient.

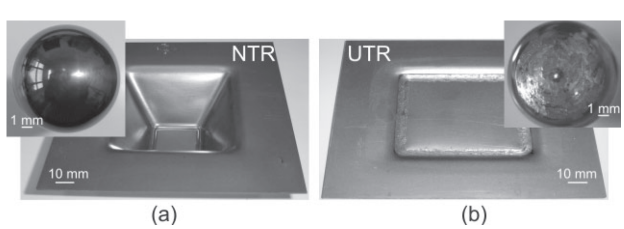

Fig. 13. *The uncoated cemented carbide forming tools and workpieces after SPIF: (a) natural tool rotation – NTR and (b) unnatural tool rotation - UTR*

However, if appropriate adhesion between the forming tool and coatings could be achieved the coatings on the basis of carbon (DLC) seem to be the best solution for improving the tribological properties by incremental sheet metal forming processes, because they may restrict or even eliminate the usage of commonly used lubricating oils, which for great pretending forming operations usually involve unhealthy additives.

In the future the investigations will be oriented to improve DLCs long-term stability for SPIF contact condition, either by increasing its load-carrying capacity, improving its adhesion, making it thicker or changing the substrate material.

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