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DOI:
10.1016/j.proeng.2017.10.1046

Citation for published version (Harvard):
Zheng, K, Dong, Y, Dong, H, Fernandez, J & Dean, TA 2017, 'Investigation of the lubrication performance using WC: C coated tool surfaces for hot stamping AA6082', *Procedia Engineering*, vol. 207, pp. 711-716. https://doi.org/10.1016/j.proeng.2017.10.1046

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 207 (2017) 711–716

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on the Technology of Plasticity, ICTP 2017, 17-22 September 2017, Cambridge, United Kingdom

Investigation of the lubrication performance using WC: C coated tool surfaces for hot stamping AA6082

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Abstract

This paper presents the lubrication performance of WC: C coated tool surfaces used in hot stamping process of AA6082. A range of cylindrical deep drawing experiments were performed to determine the required minimal lubricant amount under coated and uncoated tooling conditions. In addition, effects of process variables, forming temperature and speed, on the lubrication performance were investigated. The results have shown that the advanced WC: C Diamond-like Carbon (DLC) coating could significantly reduce the use of lubricant for hot stamping. The required amount of lubricant for successful forming decreased with increasing forming speed and decreasing forming temperature. The lubrication mechanisms under different forming conditions were discussed also.

Keywords: WC: C coating; Hot stamping; Aluminium alloy; Lubricant

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Peer-review under responsibility of the scientific committee of the International Conference on the Technology of Plasticity.
10.1016/j.proeng.2017.10.1046

1. Introduction

In recent years, solution Heat treatment, cold die Forming and Quenching (HFQ®), as a leading hot stamping process of aluminium alloys, has gained increasing popularity among the automotive and aerospace industries [1]. Compared with conventional cold stamping processes, the die surface and approaching surface region are subjected to high temperature and stress conditions during hot stamping. Most defects or failures of tool material originate from these regions. In addition, friction is normally high at the interface between work-piece and die surface at elevated temperatures. Therefore, the use of high temperature lubricant is currently indispensable [2]. However, the requirement of pre-lubrication on the stamping dies and post-cleaning of stamped parts reduces the production efficiency and increases the manufacturing cost. To avoid the use of lubricant, surface coating, such as hard ceramic coating or solid lubricant coating, can be used on the tool surfaces to improve the tribological performance. Nie et al. [3] investigated the tribological and wear behavior of Plasma Nitriding (PN) treated cast iron using a pin-on-disc tribology test. The results have shown that the PN treatment could increase the hardness and wear resistance of cast iron significantly. DLC coatings are believed to exhibit better tribological performances than the Physical Vapor Deposition (PVD) hard coatings, such as CrAlN and TiN coatings. Gharam et al. [4] found that the friction coefficient between W containing DLC (W-DLC) and 319 Al was decreased to 0.12 with increasing the temperature to 500 °C. The reason of decreased friction coefficient was believed to be achieved by the low frictional properties of WO_3 contained in the transfer layer formed at 400 °C and 500 °C. Dong et al. [5] compared the lubrication performances of different coating treatments. The WC: C coating exhibited the best lubrication performance for untreated cast iron under either cold or hot stamping condition, which indicates the potential use of WC: C coating for hot stamping aluminium alloys.

In this paper, lubrication performance of advanced WC: C coating was assessed using a practical hot stamping process, cylindrical deep drawing. Effects of different surface treatments and process variables on the minimal required lubricant amount were investigated experimentally.

Nomenclature

D_l	lubricant amount per interface area
m_l	mass of used lubricant
A	area of lubricated interface
$\hat{D}_l$	normalised lubricant amount per interface area
D_{fully}	required lubricant amount per interface area in the fully lubricated condition

2. Experimental programme

2.1. Material and tooling

The test-piece material used was AA6082-T6 condition provided by Smith Metal UK. The chemical composition is given in Table 1. For the tool material, a low-cost tool material, grey cast iron G3500, was prepared and cast according to the automotive metric standard NAAMS. The chemical composition of G3500 cast iron is given in Table 2. G3500 cast iron has a pearlite matrix with uniformly distributed and randomly orientated type #A graphite flakes. The approximate size of graphite flakes is 10×100 µm.

Table 1. Chemical composition of AA6082.

Element	Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Al
%	0.4-1.0	0.5	0.6-1.2	0.7-1.3	0.1	0.2	0.1	0-0.25	Bal

Table 2. Chemical composition of G3500 grey cast iron.

Element	C	Si	Mn	Cr	Mo	Cu	S	P	Fe
%	2.8-3.2	1.5-2.2	0.7-1.0	0.35-0.5	0.35-0.5	0-0.7	0.15	0.15	Bal

Plasma-NitroCarburising (PNC) was used as a pre-treatment to increase the surface strength of cast iron. Fig. 1(a) shows the cross-sectional SEM observation of the treated surface. An obvious PNC layer was observed on the base material which enables to increase the surface strength. In addition, to improve the tribological performance, a carbonaceous coating, W-C doped carbon (WC: C), was performed on the PNC treated tool material, as shown in Fig. 1(b). Such a treatment was conducted using Cathodic Arc enhanced PVD (CAPVD) and deposited at a temperature range: 200 -350 °C. Good thermo-mechanical properties, such as low adhesion tendency, prolonged tool life and good thermal stability, can be obtained for the tool material.

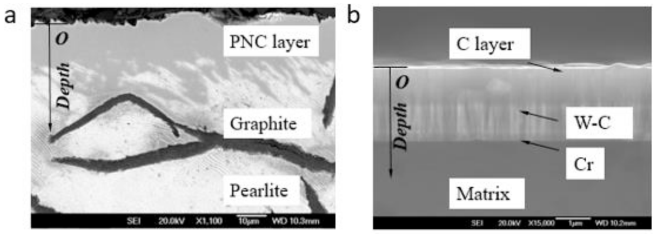

Fig. 1. SEM observations of (a) PNC treated material and (b) WC: C coated material

2.2. Experimental set-up and test procedure

A hot cylindrical deep drawing test was used to evaluate the lubrication performance of surface treated tools [6]. Fig. 2(a) shows the stamping tool set. Two pairs of die and blankholder with different surface treatments were used. One pair was duplex treated using PNC and WC: C coating, and the other pair was PNC treated only. Fig. 2(b) shows the dimensions of forming tools. The punch diameter was 100 mm. The used draw ratio of cylindrical deep drawing was fixed at 1.7 to minimize the test number. In order to test the lubrication performance of treated tool surfaces at different temperatures, an indirect hot stamping procedure was utilized as shown in Fig. 2(c). In this process, initially, the as-received T6 material was solution heat treated within a furnace at 535 °C for 2 mins. Then the treated test-piece was quickly quenched to room temperature using two steel plates at a cooling rate no less than 50 °C /s to obtain a super saturated solid solute. The quenched test-piece was reheated up to 15 °C higher than target temperatures, transferred to tools and hot stamped subsequently.

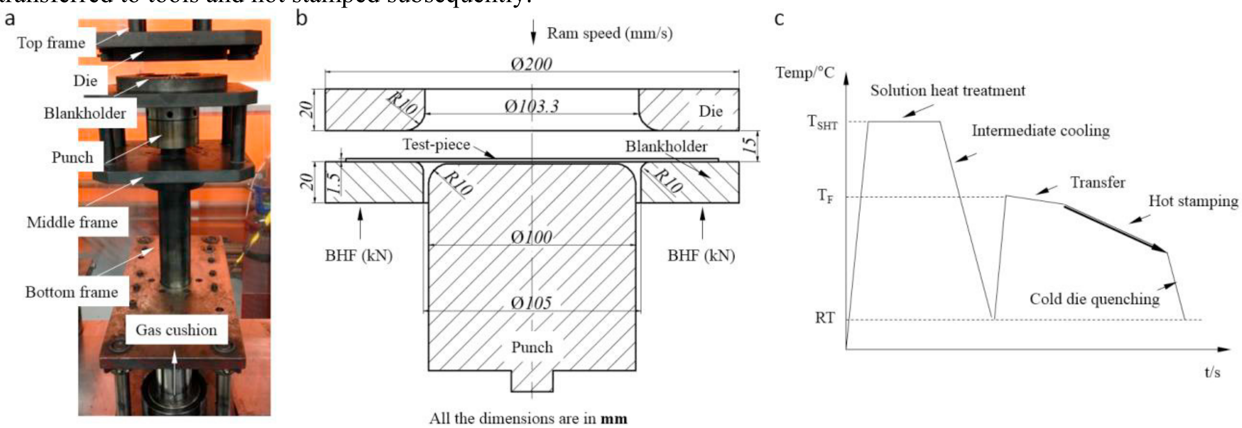

Fig. 2. (a) Experimental set-up; (b) Dimensions of tools and (c) Hot stamping procedure [6]

To minimize the experiment error, the die and punch surfaces were fully lubricated before each test. While the blankholder surface was lubricated with different amount of lubricant. The used lubricant was a commercial graphite-based high temperature lubricant for hot forming [7]. The different lubrication condition on the tool surface was presented using the amount of lubricant per interface area, D_l , as defined in Eq. (1).

$$D_l = \frac{m_l}{A} \tag{1}$$

Where m_l represents the mass of used lubricant, and A represents the contact area between test-piece and treated tool surfaces.

The weight of used lubricant was precisely measured by a balance with an accuracy of 0.01g. For the test-piece draw ratio 1.7, the magnitude of m_l guaranteed a fully lubricated condition was 0.59g, as experimentally determined. Furthermore, a normalized amount of lubricant per interface area was defined in Eq. (2) to reflect the relative lubricant use.

$$\hat{D}_l = \frac{D_l}{D_{fully}} \tag{2}$$

Where $\hat{D}_l$ represents the normalized amount of lubricant per interface area, and D_{fully} represents the amount of lubricant per interface area in a fully lubricated condition.

3. Results and discussion

3.1. Surface treatment effect

Fig. 4(a) shows the comparison of used $\hat{D}_l$ between PNC & WC: C coated and PNC treated only tool surfaces for different forming speeds at a temperature of 350 °C and blankholding force 40 kN. The dash line represents $\hat{D}_l$ for the duplex surface treatment, while the solid symbols represent those for the PNC treatment only. For the forming speed 300 mm/s, the dry lubrication condition can be achieved using the duplex surface treatment. In comparison, the used $\hat{D}_l$ of PNC treated only tool surface was around 15 %. The avoidance of lubrication of PNC & WC: C duplex surface treatment indicates an improved lubrication performance. While for the forming speed 75 mm/s, the surface treatment effect on the $\hat{D}_l$ guaranteeing successful forming was not obvious. As known to all, aluminium alloys exhibit visco-plastic feature at elevated temperatures. The material strength decreased with decreasing strain rate (forming speed) [1]. The relatively low material strength at a low forming speed required a better lubrication condition to guarantee the success of forming. Therefore, a greater amount of lubricant was still required for either PNC & WC: C or PNC treated only die surface to guarantee a successful forming.

Fig. 4(b) shows the comparison of two different surface treatments on the used $\hat{D}_l$ at a higher temperature, 400 °C. The forming speed was 300 mm/s and blankholding force was 35 kN. The duplex surface treatment can still guarantee a successful forming using less lubricant, while the required $\hat{D}_l$ of PNC treated only tool was much greater. The significantly improved tribological performance of duplex treatment at higher temperatures contributes to obtain a greater material ductility.

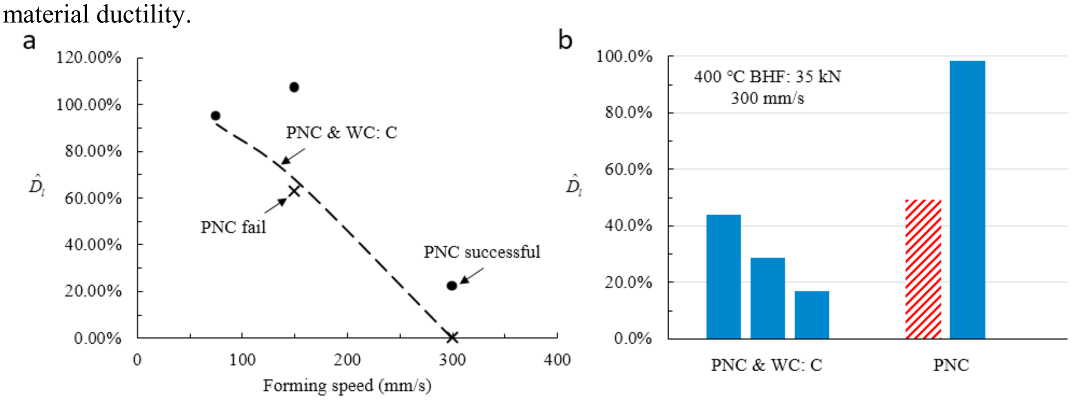

Fig. 4. Comparisons of lubrication performances of PNC & WC: C and PNC treated tool surfaces

3.2. Process variable effect

Temperature is a key variable affecting the formability of alloy and required lubricant amount for hot stamping. Fig. 5(a) shows the temperature effect on the used lubricant amount at a forming speed of 300 mm/s and blankholding force of 40 kN using the duplex surface treatment. For the temperature 400 °C, a 50 % reduction of used lubricant amount was achieved, which indicates that the good lubrication performance of WC: C coating. During flange material draw-in, the dominant lubrication mechanism was between hydrodynamic and boundary lubrication condition due to a reduced lubricant amount was used. No adhesion of aluminium alloy was observed on the tool surface after forming, one reason is that, the liquid content in the used lubricant was mainly water, the hot test-piece caused liquid evaporation to form a water film between hot test-piece and tool surface. The other possible reason might be due to the given faster and smoother running-in behaviour of contact surface [8]. However, for the temperature 450 °C, the forming was unsuccessful even using a lubrication condition with a $\hat{D}_l$ greater than 200 %. The fail of forming was mainly caused by the lower strength of aluminium alloys at higher temperatures. When the temperature is increased too high, the strength of material was too low to overcome the friction at flange region even using a sufficient amount of lubricant. Hence, the effect of duplex surface treatment on reducing lubricant is dependent on the actual forming temperature. For relatively lower temperatures, the improved lubrication performance of WC: C coating can be observed, and the used lubricant amount can be significantly reduced, such as 100 % at 350 °C. While for relatively higher temperatures, the enhanced lubrication effect using PNC & WC: C coating is unable to guarantee a successful forming due to the low strength of aluminium alloys at elevated temperatures.

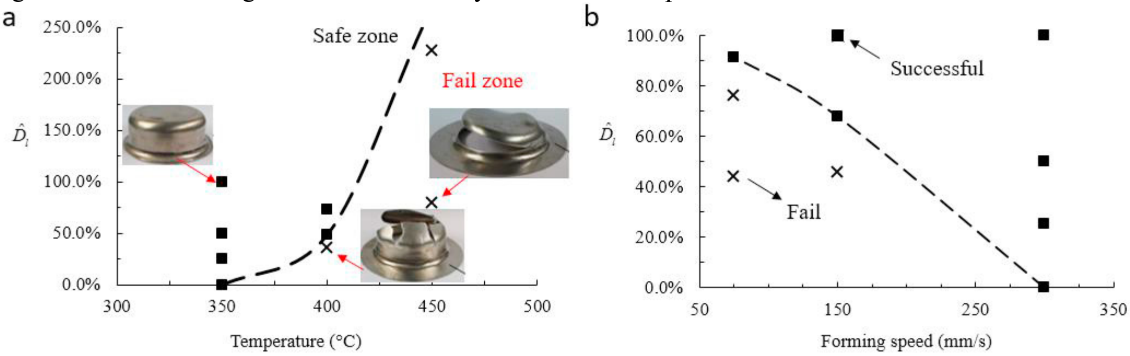

Fig. 5. (a) Temperature effect; (b) Forming speed effect

Fig. 5(b) shows the forming speed effect on the required amount of lubricant using PNC & WC: C treatment. The forming temperature was fixed at 350 °C. As shown in this figure, the required minimal lubricant amount $\hat{D}_l$ decreased with increasing the forming speed. At a very low forming speed of 75 mm/s, the minimal $\hat{D}_l$ was around 90 %. A nearly fully lubrication condition was required to guarantee the success of forming. As discussed in Section 3.1, relatively low strength of material forming at a lower speed required a greater amount of lubricant. When the forming speed increased to 150 mm/s, the minimal $\hat{D}_l$ amount can be decreased to around 60 %. Besides the increase of material strength at a higher strain rate, the other possible reason of enhanced lubrication effect using PNC & WC: C condition might be caused by the surface graphitization occurred during forming that gave a friction reduction performance [9], which needs a further microstructure analysis to confirm in the future work. Further increasing the forming speed to 300 mm/s, a lubrication free condition was achieved even the dry lubrication mechanism dominated at the interface. However, a severe adhesion was observed on the tool surface as shown in Fig. 6. which was caused by the plastic deformation of test-piece material under dry lubrication condition [10]. During sliding, hot aluminium alloy debris existed at the interface between hot test-piece and cold tool material. These particles have lower strength compared to the cold die material, resulting in the galling on the tool surface asperities. It should be noted that, such an adhesion problem was only severe for the dry lubrication condition. For the WC: C & PNC duplex treatment, the adhesion problem can be avoided efficiently at a reduced lubricant amount.

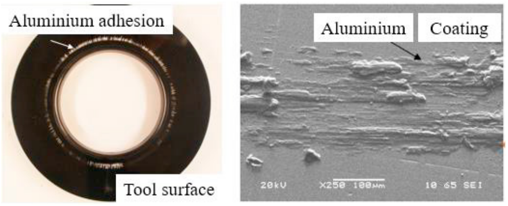

Fig. 6. Aluminium alloy adhesion

4. Conclusions

In this paper, the lubrication performance of developed PNC & WC: C duplex treated for a low-cost hot stamping tool material, G3500 grey cast iron, was characterized using practical hot cylindrical deep drawing experiments at a fixed draw ratio 1.7. The following conclusions have been obtained:

- For a temperature of 350 °C and forming speed of 300 mm/s, the lubricant free objective can be achieved, while an adhesion of aluminium alloy on the tool surface was observed due to the dry lubrication mechanism.
- The PNC treatment was believed to exhibit hardening effect on the tooling material only, while the improved tribological performance was achieved by the WC: C coating for the duplex treated tool surfaces.
- For the duplex surface treatment, the increasing of forming speed and decreasing of temperature reduced the required minimal amount of lubricant for a successful forming.

Acknowledgements

The authors thank the European Commission for their support on the H2020 project “Low Cost Materials Processing Technologies for Mass Production of Lightweight Vehicles (LoCoMaTech)”, Grant No: H2020-NMBP-GV-2016 (723517). Gratefully acknowledgements are also given to the S.C. Plasmaterm S.A. Romania for the casting and machining of tools.

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