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Experimental investigations on hot forming of AA6082 using advanced plasma nitrocarburised and CAPVD WC: C coated tools

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ABSTRACT

The use of lubricant for hot stamping process of sheet material can reduce the tendency of adhesion between work-piece and tool significantly and the friction coefficient. However, the post-process of cleaning the formed part and lubricating the tools before each stamping operation can compromise the manufacturing efficiency. It is especially challenging for hot stamping because reducing lubricant could lead to severe adhesion between tool and blank during stamping. Hence, it is desirable to develop an advanced tooling technique suitable for hot stamping processes of aluminium alloys. In this paper, an innovative tooling technology enabling hot and cold forming of aluminium with little lubricant has been developed using plasma thermochemical treatment and Cathodic Arc Physical Vapour Deposition (CAPVD) technologies. The forming performance was validated on a top-hat part stamping test to benchmark the performance of the developed tools at different forming temperature, blank-holding force (BHF) and lubrication state. The results show that WC: C coating prepared by CAPVD adequately reduced the aluminium sticking on the tool surfaces, to the extent that it achieved an 80% lubricant reduction in the hot forming stamping of a top-hat part with a drawing depth of 70 mm. The morphology of die showed that aluminium adhesion at the corner area of the die where the contact pressure doubled was still noticeable, while no severe adhesion was observed on the top flat surfaces. A further investigation of tribology on hot and cold stage tribometers was deployed to quantify the friction coefficient and wear resistance of tooling materials which were found correlated to the material's universal hardness and time-dependent adhesion rate of aluminium.

1. Introduction

High strength automotive aluminium alloys such as AA6xxx have been used for light-weight automobile body and chassis structures owing to the advantages of significant fuel saving and gas emission reduction. The poor ductility of the AA6xxx series at room temperature limits the forming of complex-shape components. In recent years, forming processes at elevated temperatures, such as superplastic forming (SPF) and warm forming have been applied to manufacture complex-shape components, however, still with limited material choices and production efficiency. Lin et al. proposed and patented a novel hot stamping process of aluminium alloys which is known as solution Heat treatment, Forming and in-die Quenching (HFQ®). The use of newly developed HFQ® technology has provided a novel forming method to form complex-shaped and high-quality heat treatable aluminium alloy components with high manufacturing efficiency suitable for mass production.

The 'key issue' of hot stamping process of aluminium alloys identified by automotive industry is the tendency of soldering the ductile and highly reactive aluminium to the tool steel. A report by NASA described the phenomena of adhesion at a molecular level (Buckley, 1975) and transferring from mono- to multi- layer film according to the electronic nature, surface energies and structural lattice disregistry. Recently, Al-tool soldering was confirmed with in-situ scanning electron microscopy by Heinrichs (Heinrichs et al., 2012). Many researches have shown that adhesion of solid surface involves mechanical anchoring, absorption and metallic bonding, which might occur spontaneously at the stamping contact surfaces as demonstrated in a postulated model (Fig. 1). To alleviate these problems, aluminium forming requires the applica-

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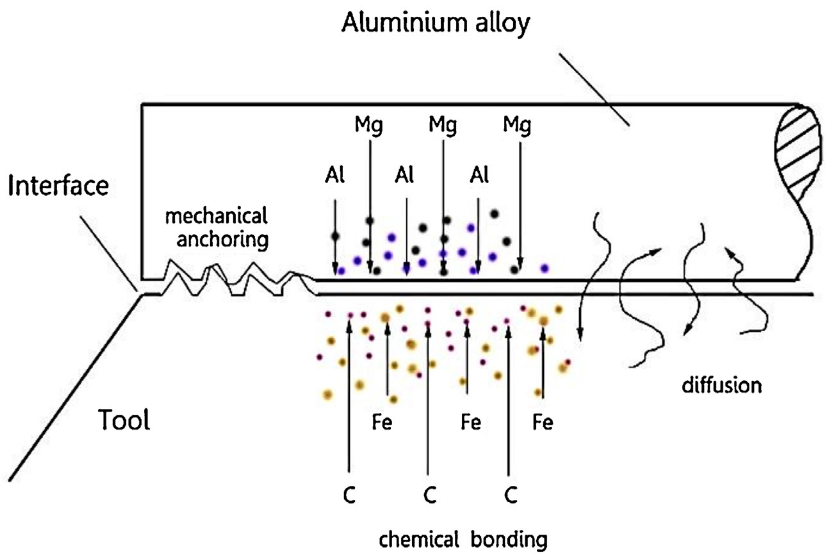

Fig. 1. A schematic diagram of the adhesion between aluminium alloy and iron.

tion of costly thermal lubricants. However, as suggested in a recent European project report (Laurent, 2007), a reduction of the use of lubricants has a meaningful impact to address ecological concerns, which makes raw materials usage sustainable and increases production efficiency. The risk of insufficient lubrication of forming tools can result in defects such as limited material extraction, tool wear and galling. Its effect on the surface quality and roughness of the formed products during lubricant free cold massive forming of aluminium was also mentioned by Wank et al. (2006). Uda et al. found that the above potential problems can be also found for the hot stamping of Al-coated steel (Uda et al., 2016). In addition, the friction force tested on hot drawing machine rise sharply during dry forming at a very early stage as well as the lubricated conditions at the end of the test. The fracture of die occurring at the punch radius area during dry forming condition was due to the lack of lubrication.

With the aim of improving the tribological performance at the interface between workpiece and tool, a feasible 'green' approach of using coating on tool surface was proposed by Vollertsen et al. (2015). For example, Hansen et al. reported that many hard coatings, such as chemical vapour deposition (CVD) carbide (TiC) and Toyota coating, have been used to treat steel tool surfaces for the drawing and restrike processes of structural components since the 1980s (Hansen and Bay, 1986); Surface heat treatment of tool steels, such as oxidation and nitriding, are frequently applied to the steel die surfaces to reduce the tool wear and prolong the tooling lifetime. A suitable tool for the mass production process is a M4 + nTiC die that stamped over 10,000 pcs B-Pillar, as suggested by (Mihail and Rodzik, 2007), and further optimisation of coating techniques are still required tremendously. To this end, very few studies have been performed on developing coatings suitable for the hot stamping of aluminium alloys due to the difficulty of producing tooling for the ductile and adhesive aluminium workpiece at high temperature.

Self-lubricating coating is another potential method to decrease the coefficient of friction (CoF) and reduce soldering between the hot workpiece metal and tool. General Motors U.S. used a solid BN film with a thickness of 50 μm on the die to achieve a CoF between 0.15–0.2 (Hanna, 2009), and successfully formed AA5083 alloy at 450 °C (Krajewski and Morales, 2004). Murakawa et al. (1995) investigated the possibility of dry-drawing process of aluminium to a small size cups of 20 mm using diamond-like carbon coated dies. In a recent report by Agarwal (Agarwal et al., 2013), the use of a reactive plasma to produce a nano-C thin film on top of hardened surface in a multi-step process was able to reduce the sliding friction force against dual phase (DP) steels. Quantitative tribological data of machining tools coated with diamond-like-carbon (DLC) for aluminium drilling (Bhowmick and Alpas, 2008) and cutting (Fukui et al., 2004), as well as using them for dry shear-stampings (Dohda and Aizawa, 2014) and dry deep drawing (Murakawa and Takeuchi, 2003) show that the unique combination of lubricity and high hardness of the carbon-based coating might be suitable for the forming tools used for lubricant-free hot stamping process of aluminium alloys.

In this study, gray cast iron was used as the tooling material owing to the low cost compared with conventional hot work tool steel. To overcome the low strength of gray cast iron compared with the hot work tool steel, the gray cast iron can be surface hardened by plasma (Dong et al., 2015) and gas thermochemical treatments (Rolinski, 1987). Hence, plasma nitrocarburising of cast iron has been developed to improve the strength and increase the lifetime of forming tools in this study. Based on a previous feasibility study of the self-lubricated tools (Dong et al., 2015), plasma nitriding and plasma nitrocarburising plus CAPVD coatings was selected as the surface engineering process of the die. The performance of the HFQ® forming technique combined with newly applied coatings on the blank-holder was examined for the first time on a top-hat shaped hot stamping testing rig using a series of controlled forming conditions. The geometry of deep-draw parts and the post-stamping morphology of die surfaces are reported. The particular friction behaviour, wear rate and hardness of tool materials were tested separately to provide a detailed root-cause analysis of the tribological phenomenon between the tooling materials and aluminium alloy.

2. Experimental design

2.1. Test-piece and tool material

Commercial AA6082-T6 condition aluminium sheet (Smiths Metal Centres, UK) with a thickness of 1.5 mm was selected as the test-piece material. The chemical composition of AA6082 is given in Table 1. Rectangular test-pieces were pre-cut by laser cutting to dimensions of 240 mm × 86 mm × 1.5 mm. These test-pieces were