Journal of Materials Processing Technology 210 (2010) 323–329

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Full length article

Warm negative incremental forming of magnesium alloy AZ31 Sheet: New lubricating method

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ARTICLE INFO

Article history:
Received 4 June 2009
Received in revised form
16 September 2009
Accepted 17 September 2009

Keywords:
Magnesium alloy
Incremental forming
Pulsed anodic oxidation
Lubrication
Coating

ABSTRACT

The present study has been undertaken in order to investigate the suitable lubricants and lubricating methods, which can be employed to form a magnesium alloy AZ31 sheet by warm negative incremental forming (NIF). For the intended purpose, Nano-$K_2Ti_4O_9$ whisker and organic binder were employed to improve the bonding strength at lubrication coating/sheet interface and lubricating properties at elevated temperatures. The Nano-$K_2Ti_4O_9$ whisker enhanced solid lubrication film and the solid graphite or MoS_2 powder-coated porous ceramic coatings by pulsed anodic oxidation (PAO) almost have the same coefficient of the initial friction about 0.07–0.1 at room and elevated temperatures, which was satisfied with friction and lubrication condition of warm incremental forming (IF) of the metal sheet. Solid graphite or MoS_2 powder-coated ceramic coatings possessed the remarkable lubrication and self-lubrication effect. These suggested lubricating methods gave an excellent solid lubrication performance and good surface quality of the formed parts in warm IF process of the metal sheet.

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1. Introduction

It is difficult to form hard-to-form sheet metals (for example, magnesium alloy and titanium alloy) by the single point incremental forming (SPIF) process due to the low formability at room temperature. However, the rolled AZ31 alloys offer good mechanical properties with good balance between strength and ductility, and excellent formability at elevated temperature because non-basal slip systems become active in addition to basal slip such as hot drawing forming (Hai et al., 2008), gas bulging forming (Kim et al., 2008) and warm SPIF process (Ji and Park, 2008; Ambrogio et al., 2008).

A thorough deliberation may reveal that the lubrication is not so simple when the magnesium alloy sheet is formed. For applying the lubricant to the surface of sheet metal and ensuring its presence throughout the whole forming process in warm SPIF of magnesium alloy sheet, the lubricant must be special, which will withstand the local deformation and high temperature, and will not be squeezed out from the mating surfaces. If the lubricant is not selected by keeping in view the specific characteristic of the SPIF process, the metal sheet may peel off.

In the cold incremental forming of soft metals, such as pure aluminum and low carbon steel, mineral oils can provide sufficient lubrication to produce parts with an acceptable surface quality, as shown in literature (Kim and Park, 2002) However, the preliminary experiments were carried out by employing mineral and machine oils as lubricants in the hot forming conditions which thinned out and did not serve the purpose well due to low viscosity and low heat-resistance. In this category, solid graphite and MoS_2 (these lubricants have smaller coefficient of friction than the other solid lubricants such as boron nitride, etc.) were investigated in detail. As the solid lubricant, the graphite has been applied for a long time. In the sol–gel graphite solid lubrication coating, the graphite was as solid lubricant and Zn was as a platform for graphite powder that enhanced the bonding strength with substrate (Wang et al., 2005). Solid lubricants are highly effective because of their excel-

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doi:10.1016/j.jmatprotec.2009.09.018

Table 1
Chemical composition and room mechanical properties of AZ31 alloy.

Chemical composition (%)						σ_s (MPa)	σ_b (MPa)	δ (%)
Al	Zn	Mn	Si	Fe	Mg			
3.0	0.95	0.28	0.22	0.012	Other	110–175	240–260	22–26

lent lubricating ability in the wide temperature range, from room temperature to 400 °C. However, the solid lubricants are generally coated with a binder on the workpiece by conventional spraying, their original solid-lubricating abilities are lost with a lubricating life (Hanada et al., 2005). Properties of MoS_2 coatings can be improved by the codeposition of titanium (Jing et al., 2004). The parts of pure titanium sheet in NIF with good surface can be realized by using the anodic oxidation (AO) and the paste of molybdenum disulphide (MoS_2) with petroleum jelly (Hussain et al., 2008). The cone parts of titanium alloy ($TiAl_2Mn_{1.5}$) sheet with AO were processed successfully by electric hot method and using solid MoS_2 powder dusted on the surface of the sheet metal as lubricant in SPIF (Fan et al., 2008).

Well known, the ceramic coating by micro-arc oxidation or PAO is classified into a porous loose over-coating and a compact bulk coating (Guo and An, 2006; Jin et al., 2006). Therefore, porous ceramic coating on the metal sheet may be coated by application of the solid lubricant so that the lubricant particles can be retained in the pore of the coating or absorbed by the porous coating. But up to the present-day, no literatures report the research on the solid lubricant film or coating prepared by the PAO method for warm SPIF of the magnesium alloy sheet.

In this present paper, sheet blank with and without PAO ceramic coating was used to investigate the effect of lubrication coating and its categories on the surface quality of the formed parts. The main objective of the research contained the proper lubricants, lubricating properties and novel lubrication method for warm negative incremental forming of the magnesium alloy sheet.

2. Experiment

2.1. Experimental materials

The cross-rolling sheet with thickness 0.8 mm of magnesium alloy AZ31 was used as the experimental material in the present study, its composition and room mechanical properties are given in Table 1.

2.2. Test devices and method

The experimental device is CNC IF machine NH-SK1060 based on UG. The sheet is fixed by upper and lower blank holder, forming tool controlled by CNC machine with CAD/CAM implements continuous plastic forming. In the CNC machine, three-dimensional profiles are formed by the single point moving between the heated sheets and forming tool. The tool tip moves along the inner surface of the model and from edge to center, until forming completes, the edge of sheet is fixed. Some important process parameters used in the experiments are as below: tool material = high-speed steel; radius of the hemispherical tool head = 6 mm; feed step size = 0.2 mm/revolution; horizontal feed rate = 2000 mm/min; forming angle = 55°; sheet temperature = 200 °C; sheet blank size = 100 mm × 100 mm square.

According to the results of the previous investigations, some cone parts with excellent surface such as square, round and rotary were gradually formed on a CNC IF machine with heating equipment under experimental conditions, and the influence of anisotropy of the magnesium alloy AZ31 sheets fabricated by various methods on formability and the surface quality parts in the SPIF process at different temperatures were systematically investigated (Zhang et al., 2009).

The friction coefficient of the solid lubricants from room temperature to high temperature was measured in an air environment on UMT-2 multi-function friction and wear tester. The microstructures of the AZ31 alloy sheet before and after warm IF were analyzed by field emission scanning electron microscope (SEM) JEOL JSEM-7001F.

In the warm incremental forming, there are no unified criteria which can be used to evaluate the application of lubricant and its contribution on the formed part quality. This research mainly uses the following way to evaluate lubricating quality: by the initial friction coefficient of the lubricant and according to the surface quality of the formed parts without any nicks.

3. Results and discussion

3.1. Lubricating coatings preparation

The preparation processes of the five lubricating coatings (denoted by “A”, “B”, “C”, “D” and “E”, respectively) (Table 2) are various. The main processes are described as follows.

To begin with, for the non-coated sheet, solid MoS_2 (method “A”) or graphite (method “B”) in the form of powder was dusted on the surface of the sheet as lubricant, which was implemented artificially, in such way the tool tip nearly submerged in the lubricant up to the depth of 6 mm and the lubricant was not squeezed out from the mating surfaces, so this way can keep continuous lubrication between the tool tip and sheet surface as shown in Fig. 1(a), otherwise, it led to discontinuous lubrication and rough inner surface of the part due to the fact that graphite particles did not adhere to the smooth surface of the sheet and freely moved with tool together that resulted in direct friction of the tool tip with the sheet surface, and forming rough nicked surface of the parts.

Graphite as the solid lubricant is appropriate for metal forming from the practical and costly viewpoints. Lubricant and lubricating method “C” were: lubrication mixture consists of Nano-$K_2Ti_4O_9$ whisker 1–20%, solid graphite lubricant 6–30%, antioxidant (P_bO) 2–5%, organic binder (phenolic resin or polyurethane) and thinner (ketone) 45–90%; Phenolic resin or polyurethane can guarantee to bond MoS_2 or graphite powder on the sheet metal surface. Lubrication mixture was sprayed directly on the surface of the sheet at room temperature with pressurized gas and then was dried by heating. Organic binder improved the bonding strength between solid lubricant and substrate, and the microstructures and friction properties of the sprayed sheet were examined. It is observed

Table 2
The lubricants and lubricating methods.

Sheet	Experiment no.	Lubricant	Application method	Quality of formed surface
Without PAO	A	MoS_2	Tool submerged in the lubricant	Surface roughness and nick
	B	Graphite	Tool submerged in the lubricant	Surface roughness and nick
	C	$K_2Ti_4O_9$ + graphite	Sprayed	Good
With PAO	D	MoS_2	Bepowdered	Good
	E	graphite	Bepowdered	Good

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