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Case study

Study of lubrication and wear in single point incremental sheet forming (SPIF) process using vegetable oil nanolubricants

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ABSTRACT

The aim of the present study focuses on investigating the performance that sunflower and corn oils, added with 0.0125, 0.025, 0.05 and 0.1 wt% of SiO_2 nanoparticles, have when these are used as lubricants during Single Point Incremental Sheet Forming (SPIF) process of 6061 aluminum sheet alloys. In an attempt to explain the differences between friction conditions, the Stribeck curve was used to address the influence that the reinforced lubricants have on the friction and roughness values attained during SPIF process of the aluminum alloy samples. To study the wear effects that the nanoparticles have on the surface samples, the Scanning Electronic Microscope (SEM), Energy-Dispersive X-ray Spectroscopy (EDS) techniques were used to observe the surface morphology and chemical composition. Fourier Transform Infrared Spectroscopy (FTIR) technique was used to study the interaction of the SiO_2 nanoparticles with vegetable oils. Experimental results showed a significant surface wear reduction when 0.025 wt% of SiO_2 nanoparticles are added into the vegetable oils.

1. Introduction

Aluminum alloy 6061 is widely used in automobile, aerospace, and marine components due to its good strength, light weight and better corrosion properties [1,2]. This aluminum alloy has been typically used to manufacture rapid prototypes through single point incremental sheet forming (SPIF) process. This manufacturing process is popular in industry because manufacturing sheet metals can be accomplished in any facility having a three-axis CNC mill without the need of using a die [3–5].

SPIF process has shown to reach higher components formability when compare to deep drawing however, this process is still under study since effects such as spring back, deformation mechanisms, and residual stresses among others, are not fully understood. Furthermore, wear and surface finishing has not been address yet, when using reinforced vegetable oils during SPIF process of sheet metal parts. Hussain et al. found in [6] that the type of lubricant and the lubrication regime directly affect the product surface quality. Sornsuwit et al. concluded in [7] that the surface roughness was influenced by SPIF process parameters such as the forming depth, the wall angle, and the sheet metal thickness. It is evident that the use of lubricants is essential to increase tool life and to reduce wear and surface roughness effects. For instance, Lu et al. found that friction effects between the tool and the metal sheet plays a major role in the surface finishing and the material deformation capability [8]. Wan Nik and co-workers concluded that the rheology and fluid dynamics of bio-edible oils plays and important role in improving heat distribution and removing waste materials [9]. Unfortunately, most lubricants are petroleum based. These petroleum oils can harm the human skin, causing irritation and allergies due to the presence of glut amount of microbial toxins [10].

Although vegetable oils have several properties that are similar to mineral oils such as high viscosity index, high lubricity, low volatility, low toxicity and high biodegradability [11–16], these can not be used as lubricants if high load magnitudes are applied during manufacturing processes [17]. However, in recent years, many studies have been done when nanoparticles are used to reinforced lubricants. For instance, Saurín et al., described that the reduction of friction and wear are related to the nanoparticle characteristics such as size, shape and concentration [18]. Murshed et al. [19] reported that the extreme pressure capability of a nanolubricant could be two times higher than that of pure oil and hence, nanolubricants can improve lubrication performance by reducing contact effects between metal surfaces. Therefore, different metallic oxides such as TiO_2 [20,21], ZrO [22,23], and SiO_2 [24] have been used as lubricant additives.

The aim of the present work focuses on studying how wear resistance and lubrication effects are modified during SPIF process

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of aluminum 6061 sheets alloys when 0.0125, 0.025, 0.05 and 0.1 wt% of SiO_2 nanoparticles are added into sunflower and corn oils. The *Stribeck* curve adapted for the SPIF process is used to explain the evolution of the lubrication regimes during the manufactured of sheet aluminum alloys samples. Experimental techniques such as Scanning Electronic Microscope (SEM) and Energy-Dispersive X-ray Spectroscopy (EDS) were used to characterize the surface samples. To address the issue regarding the interaction of SiO_2 nanoparticles that were added into the vegetable lubricants, the Fourier Transform Infrared Spectroscopy (FTIR) technique was used.

2. Experimental details

2.1. SPIF process

A SPIF fixture set up shown in Fig. 1 was used to generate a pyramid frustum (generatrix) on aluminum metallic sheets. As illustrated in Fig. 1, the metallic sheet was placed between the clamping and the top plates. Here, it was considered a blank holder with the dimensions of 150 × 150 mm, with an effective workable area of 120 × 120 mm. A wide variety of experimental tests were performed in a Kryle CNC 535 3-axis milling machine equipped with a Kistler piezoelectric dynamometer, and a charge amplifier connected to a data acquisition system. The forming forces were measured only along the axes of the tool (F_a= the along SPIF force; F_v= vertical force).

The tests consisted on incrementally forming the pyramid frustum with variable wall angle at each incremental forming depth, as shown in Fig. 2. This part geometry has been extensively used in previous works to study SPIF processes on metallic materials [25].

2.2. SPIF Parameters

During the experimental tests, a 10 mm diameter hemi-spherical, high speed steel (HSS), tool head with horizontal feed rate of 3000 mm/min, and incremental vertical step size (Δz) of 0.5 mm, were considered.

2.3. Materials

6061 aluminum alloy sheets were used to test the effects of vegetable oils reinforced with SiO_2 nanoparticles during SPIF process. These sheets were trimmed to the size of 150 mmx150 mm with an initial thickness of 1.5 mm. Two different lubricants were analyzed: sunflower and corn obtained from AGYDSA Company. The properties of the lubricants are summarized in Table 1. During the SPIF process of each sample, the amount of 16 ml of oil was used. The SiO_2 (10–20 nm) nanoparticles, supplied by Sigma-Aldrich, were added into the base vegetable oils at the different composition percentages of 0.0125, 0.025, 0.05 and 0.10 wt%. These small concentrations were selected since in a previous research work [26], it was found that small concentrations of nanoparticles could enhance lubricants effects.

2.4. Nanolubricant preparation

Nanolubricants were prepared following the process described by Taja-Tijerina et. al. in [27]. Nanoparticles of SiO_2 were dispersed using a Cole-Parmer 500-W ultrasonic probe sonicator with a fixed frequency of 20 kHz for 10 min. Thereafter, nanoparticles were homogeneously dispersed using an extended bath sonication (~3–4 h). A Metason 120 T sonicator with an output power of 70 W was used for this purpose, and the water bath was maintained at the room temperature of 25 °C.

2.5. Sample characterization

The scanning electron microscopy (SEM) was used to investigate wear on the surface of the forming samples. Therefore, SEM samples characterization was carried out on a JEOL JSM 6490LV equipment using EDS to analyze the wear mechanisms promoted during SPIF process, and the composition of elements at the different phases of the aluminum alloy. Roughness measurements were performed by using Surftest SJ-210 Mitutoyo equipment. All collected data will be discussed later on.

2.6. Evaluation of friction and wear

The wear tests were conducted during SPIF process and under lubricated sliding conditions on the surface of previously cleaned specimens. All the tests were run for a period of 9 min. and the mass loss was obtained by a gravimetric method. The tool sliding distance on the aluminum sheet during SPIF process was 2000 m, and an average of 3 samples were tested for each reinforced oil concentration. The friction coefficient is difficult to calculate since the measured horizontal force contains not only the friction but also the forming force. Alternatively, a friction indicator μ_i is defined in the analysis to evaluate the friction condition. The friction indicator was calculated using the following equation [28]:

$$\mu_i = \frac{F_f + F_l}{|F_v|} = \frac{F_a}{|F_v|}, \tag{1}$$

where F_f, F_l, F_a, and F_v are the friction, the load, the along, and vertical forces, respectively.

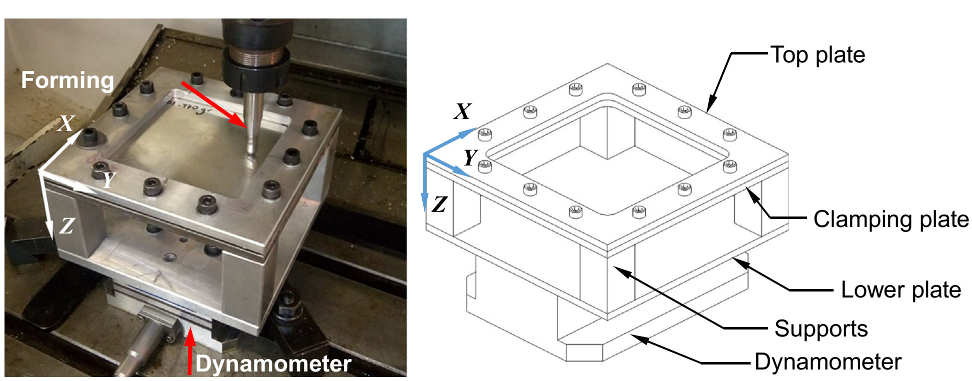

Fig. 1. SPIF experimental setup mounted on a Kyle CNC 535 3-axis milling machine.