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Research Paper

Optimizations of electric current assisted chemical milling condition of 2219 aluminum alloy

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ABSTRACT

The chemical milling condition of 2219 aluminum alloy is investigated in the NaOH + Na_2S + triethanolamine + Al^{3+} alkaline system by the assistance of electric currents. The purpose is to study the influences of electric current densities on both the milling rate and the surface roughness of 2219 alloy under different temperatures, NaOH concentrations and additions of inhibitors. The experiments are carried out under the given requirement that the milling rate is from 0.08 mm/min to 0.14 mm/min and the surface roughness is less than 0.65 μm. The reaction temperature of the chemical milling process can be reduced by 10 °C with the application of current densities in the range of 0–20 mA/cm^2. The concentration of NaOH in the alkaline system can be reduced from 180 g/L to 120 g/L with the application of current densities in the range of 0–60 mA/cm^2. With the addition of Na_2SiO_3, Na_2CO_3 and Na_2SnO_3 inhibitors in the alkaline system, both the milling rate and the surface roughness of 2219 alloy decrease. The region enclosed with the suitable NaOH concentration and current density expands and moves towards the high current density.

1. Introduction

Chemical milling is a non-traditional machining process, by which materials are removed in strong corrosive solutions and components with complex geometries and accurate dimensions can be machined (Çakir, 2008). In addition, using chemical milling to realize a highly efficient and environmentally-benign manufacturing is presented and evaluated by McCallion (1987). As a result, chemical milling is widely applied in the manufacturing of steel or aluminum alloy products.

Sanz (1956) has firstly introduced chemical milling for industry, classifying the chemical milling solutions used for aluminum alloys into two groups. One group is the acidic system, which is mainly composed by ferric nitrate or ferric chloride. Chambers (2000) has invented a viable etchant composed of ferric nitrate and disclosed the relationship between the etch rate and the sufficient concentration of ferric compounds. However, researches on the surface quality affected by operating conditions are lacking. Çakir (2008) has described the chemical milling of aluminum alloys in ferric chloride at different operating temperatures. In the acidic system, the chemical milling of aluminum alloys can be operated at a relatively low temperature (20–50 °C), while the processed aluminum alloy has a high surface roughness (about 7–10 μm). The other group is the alkaline system, which consists of sodium hydroxide and dissolved aluminum with the addition of Na_2S, triethanolamine (TEA), $NaNO_3$, Na_2CO_3, etc. Gross (1986) has reported a chemical milling solution which contains sodium hydroxide, nitrate and ethylene glycol. This solution has an advantage in machining aluminum alloys with high compositions of copper or zinc, e.g., 2219 aluminum alloy. However, the operating temperature needs to be maintained at 90 °C in this chemical milling solution. Matsumoto et al. (2007) have demonstrated a chemical milling method to produce density-graded aluminum foams by using a pH-temperature controlled NaOH bath. This work focuses on researching the influences of processing parameters on the microstructure. The result shows that a delicate morphology can be obtained by elevating the pH. A comparison made by Chandler (2008) has also revealed the same trend. Compared with the chemical milling process in the acidic system, the process in the alkaline system results a better surface roughness with a higher temperature (55–65 °C). To further use the advantage of the alkaline system in the surface quality, efforts have been made on promoting the surface quality of samples processed in the alkaline system by altering solution compositions and operating conditions. The works in the literature have contributed to the knowledge of the influences of processing parameters on the machining quality of chemical milling. Smooth surfaces and applicable milling rates can be obtained by adjusting parameters. Li et al. (2015) have recently presented the optimization of a chemical milling solution for 2219 aluminum alloy. This solution is composed of NaOH, Na_2S, TEA, and Al^{3+}. In this solution, a low surface roughness (0.5–0.8 μm) of 2219 alloy can be obtained.

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However, a high reaction temperature (80 °C) and a high NaOH concentration (160–200 g L^{-1}) are still required for the chemical milling process. In order to improve the operating condition of chemical milling processes, the reaction temperature and the NaOH concentration for the alkaline system need to be reduced.

Electrochemical machining (ECM) is a well-established technology for shaping metals to produce complex parts in aerospace, defense and medical industries (Pajak et al., 2006). Lohrengel et al. (2016) have recently reported the mechanisms of the anodic dissolution during electrochemical machining. The mechanisms can be classified by the changing of surface conditions during ECM. The removal rate of the ECM process is controlled by the anodic dissolution of materials at high current densities of up to 100 A/cm^2. In the study reported by Meichsner et al. (2016), the pulse current is introduced into ECM to achieve fast removal rate and precise control. The machining precision of products can be improved by the application of pulsed currents, laser beams, charge modulations, etc. However, the research on the combination of chemical milling and electrochemical machining for shaping materials remains an open direction.

The objective of this work is to explore the chemical milling conditions of 2219 aluminum alloy in the alkaline system under different electric current densities. The milling rate and the surface roughness of 2219 alloy are investigated under different milling conditions. With the combination of chemical milling and electrochemical machining, not only the operating conditions such as the reaction temperature and the NaOH concentration but also the composition of alkaline system can be optimized to improve the safety and the operability of the chemical milling process.

2. Experimental

2.1. Materials

The chemical compositions of 2219 aluminum alloy used in this paper were shown in Table 1. A plate of 2219 aluminum alloy with the thickness of 6 mm was firstly machined to samples with the dimensions of 20 mm × 20mm × 6 mm, and then abraded by water emery papers from 200 to 1500 SiC grit. After cleaned with ethanol and acetone, the samples were dried for chemical milling.

2.2. Electric current assisted chemical milling

The reaction temperature and the NaOH concentration needed to be reduced for the safety and the operability of the chemical milling process. The purpose of this design was to explore the methods to reduce the temperature and the NaOH concentration. Thus, the ECM method of imposing electric currents was worth a try. In the experiment, the electrolyte solution for chemical milling was mainly composed by 120–180 g L^{-1} NaOH, 5 g L^{-1} Na_2S, 60 g L^{-1} TEA and 25 g L^{-1} Al^{3+}. This solution was the optimal milling solution with the lowest surface roughness of 2219 aluminum alloy as demonstrated by Li et al. (2015). In the proposed experiment, inhibitors were added into the above solution to adjust the milling rate of the alloy. As reviewed in the literature, both Triki et al. (1979) and Lopez-Garrity and Frankel (2014) investigated that sodium silicate could be an effective inhibitor for aluminum in the alkaline system due to the formation of films on metal surfaces. Sodium carbonate was reported as a surface-finishing agent in the etching solution for aluminum alloys by An et al. (2002). Sodium stannate was also an inhibitor for aluminum in alkaline media as illustrated by Rosilda et al. (1994). Three inhibitors with different compositions of 0.02% Na_2SiO_3, 0.02% Na_2SiO_3 + 10% Na_2CO_3 and 0.03% Na_2SnO_3 were selected as the additives in the proposed experiment. The results from the immersion tests indicated that the inhibition efficiencies of 0.02% Na_2SiO_3, 0.02% Na_2SiO_3 + 10% Na_2CO_3 and 0.03% Na_2SnO_3 for 2219 alloy in the above alkaline solution were 15%, 20% and 32%, respectively.

Electric currents with the density of 20, 40, 60, 80, 100 mA/cm^2 were imposed on the 2219 aluminum alloy. Pulse currents were used in the proposed experiment, following a cycle of 15 s forward current and 5 s backward current. The sample of 2219 aluminum alloy with a working area of 12.8 cm^2 was used as the working electrode, and a graphite rod was applied as the counter electrode.

The reaction temperatures of the milling process were 20, 40, 60 and 80 °C controlled by a water bath. After processed for 60 min, the samples were taken out from the solution, and then treated in 30% (wt.%) HNO_3 solution for glaring until the black precipitations absorbed on the surface were dissolved completely. All the chemical reagents used above were in analytical grade, and the chemical milling solution was prepared with distilled water. After cleaned with water and dried, the samples were well prepared for surface characterizations.

2.3. Characterizations

The surface roughness of 2219 aluminum alloy after chemical milling was measured by the Talysurf tester (Taylor-Hobson Form Talysurf i120). The chemical milling rate v was calculated by the equation formulated as follows,

$$v = (m_1 - m_2)/(\rho \cdot a \cdot b \cdot t) \tag{1}$$

where m_1 (g) and m_2 (g) represented the weights of the samples before and after milling, respectively; ρ (g cm^{-3}) represented the density of 2219 aluminum alloy; a (cm) and b (cm) represent the length and width of the samples after milling, respectively; t (min) represented the processing time of chemical milling. The unit of the chemical milling rate obtained from the proposed equation was cm/min. For the simplicity of the following discussion, the unit was changed from cm/min to mm/min. After the characterizations, the experimental results and further discussions were presented in the following section.

3. Results and discussion

3.1. Effects of the temperature under electric currents

The milling rate and the surface roughness of 2219 aluminum alloy under different current densities and temperatures are illustrated in Fig. 1. As shown in Fig. 1a, the milling rate of 2219 alloy varies from 0.03 mm/min to 0.27 mm/min. The milling rate increases obviously as the current density and the temperature increase. As shown in Fig. 1b, the surface roughness of 2219 alloy varies from 0.55 μm to 1.39 μm. The surface roughness increases as the current density increases under the same temperature. While under the same current density, the surface roughness fluctuates as the temperature increases. The surface roughness at 20 °C and 60 °C is larger than that at 40 °C and 80 °C.

Based on the data in Fig. 1, three-dimensional graphs for the behaviors of the milling rate and the surface roughness of the 2219 alloy with respect to the current density and the temperature are illustrated in Fig. 2. By considering the practical applications in the industry, DeGarmo et al. (2003) have described in the publication that the

Table 1
Chemical compositions of 2219 aluminum alloy (wt.%).

Cu	Si	Fe	Mn	Mg	V	Zr	Zn	Ti	Others	Al
5.8–6.8	≤0.20	≤0.30	0.20–0.40	≤0.02	0.05–0.15	0.10–0.25	≤0.10	0.02–0.10	≤0.15	Bal.