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A comparative study on process potentials for frictional stir- and electric hot-assisted incremental sheet forming

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Abstract

Incremental sheet forming (ISF), as an advanced forming technique, has received increasing interest from both academia and industry due to its improved formability, greater process flexibility and reduced energy consumption in its life cycle. However, with the growing application of lightweight alloys with very limited material elongation, conventional ISF inevitably encounters challenges in processing these alloys at room temperature, especially in forming magnesium and titanium alloys. Therefore, heat-assisted ISF techniques have been proposed to further enhance material formability at elevated temperatures. In this work, two heat-assisted ISF approaches, frictional stir- and electric hot- assisted ISF, have been employed to process the hard-to-form materials in terms of the flexibility and local dynamic heating. The temperature evolution and corresponding forming force at different feed rates of these two techniques, is investigated in detail to build up a processing window. In addition, process capabilities are compared by forming different geometrical shapes of magnesium alloy AZ31B of 1.4 mm sheet thickness. The investigation results show the pros and cons of frictional stir- and electric hot- assisted ISF. Frictional stir-assisted ISF is more efficient than electric hot-assisted ISF under current experimental results. However, electric hot-assisted ISF has faster heating rate which makes this technique less dependent on the component geometry.

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Keywords: Incremental sheet forming (ISF); Hot forming; Frictional heating; Electric heating; Process capability

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1. Introduction

Incremental sheet forming (ISF) has received the ever increasing interest from both academic and industrial communities in recent years. ISF has greater process flexibility and enhanced material formability compared to conventional sheet metal forming processes. However, with the increased use of lightweight materials, ISF inevitably encounters challenges in processing these so-called 'hard-to-form' materials. In order to improve the material formability, a series of studies have been conducted to carry out the ISF process at warm or hot conditions by various approaches such as frictional stir-assisted ISF, electric hot-assisted ISF and laser-assisted ISF. Of all the developed processes, the frictional stir- and electric hot- assisted ISF processes show superior advantages in terms of process flexibility, equipment cost and localized heating during dynamic movement (Xu et al., 2013).

Otsu et al. (2010) first introduced the concept of frictional stir into the ISF process. They studied the formability improvement in forming AA5052-H34 aluminum alloy sheets under tool rotation speeds up to 10000 rpm. The formability improvement of magnesium alloy AZ31, AZ61 and AZ80 in frictional stir-assisted ISF was investigated by the same procedure (Otsu et al., 2011). In both cases, the results indicated that material formability dramatically enhanced because of thermal effect and dynamic recrystallization when tool rotational speed was greater than 7000 rpm. Similarly, Buffa et al. (2012) observed a significant formability enhancement when forming AA1050-O, AA1050-H24 and AA6082-T6 at the tool rotation speed of 8000 rpm, and then built up formability curves at varying rotation speeds. Xu et al. (2013) investigated different effects of friction and frictional heat in formability improvement of AA5052-H32 aluminum alloy sheets at a wide range of tool rotation speeds from 250 to 7000 rpm, and discussed the influence of laser surface textured forming tools on forming forces, temperatures and the corresponding formability.

In the investigation of the electric hot-assisted ISF approach, Fan et al. (2008) applied DC current through the forming tool to incrementally form the titanium alloy sheet by locally heating the deformation area, where the generated heat flux improved the ductility of material. Moreover, Ambrogio et al. (2012) proposed a parameter termed as 'specific energy' which is related to contact resistance, current density, tool feed rate, sheet thickness and arch of contact, to quantify the heat supplied to the material during the forming. Bu defining this parameter, the formable windows of AA2024-T3, AZ31B-O and Ti6Al4V were identified. Sy and Nam (2013) developed an electrically assisted ISF system with a DC power source and processed both AA5055 and AZ31 material sheets. In their study, they directly connected two electrodes to metal sheets to generate a homogeneous heating zone over the whole forming area.

The above investigations demonstrated the enhanced process formability by applying the frictional stir- and electric hot- assisted ISF in the processing of various lightweight, hard-to-form materials. However, process limitations and adaptability are rarely discussed in these studies. Limited work can be found on comparative studies to provide sufficient evidences to confirm which method is superior to the other, thus more suitable for industrial application. In this work, two heat-assisted ISF methods, including the frictional stir- and electric hot- assisted ISF processes, have been employed to form the hard-to-form materials to compare their process flexibility and local dynamic heating. The temperature evolution and corresponding force at different feed rates using these two techniques, is investigated in detail. In addition, process capabilities are compared by forming different geometrical shapes with magnesium AZ31B sheets. The results suggest that electric hot-assisted ISF is more efficient and controllable, and is less dependent on component geometry.

2. ISF with localized heating

2.1. Frictional stir-assisted ISF

In frictional stir-assisted ISF, heating is generated by the rotating tool. The friction generated heat Q_i at an arbitrary contact point i on the tool-workpiece interface can be simply described in Eq. (1).

$$Q_i = f_i V_i t_t = f_i \left(r_i \omega + v \right) t_t, \tag{1}$$

where f_i and V_i are the frictional force and the resultant linear velocity at contact point i, respectively. In Eq. (1), r_i represents the corresponding radius of contact point i, ω is the tool rotational speed, v is the feed rate of the forming tool and t_t is the duration of contact time at point i. It assumes that the radius of the contact point is 2.5mm, and the tool feed rate v increases from 1200 to 2400 mm/min when tool rotation speed ω is fixed as 5000 rpm. As a result, the corresponding V_i changes slightly from 1328 to 1348 mm/min. This means that the feed rate has very limited influence on the generated frictional heating. Additionally, f_i is proportional to normal force, i.e. vertical forming force. Therefore, if surface conditions of sheet blanks are at the same level, the higher the yield stress of sheet material, the larger the friction generated heat.

2.2. Electric hot-assisted ISF

In electric hot-assisted ISF, the heat generation usually follows the relationship in Eq. (2).

$$Q_E = I^2 R_{contact} t_t , \tag{2}$$

where Q_E is the generated heat flux, I is the applied current, $R_{contact}$ is the contact resistance between the forming tool and the sheet and t_t indicates the duration while the local material is heated up. The forming tool is continuously heated during the whole process since it is connected with one of the electrodes. Heat transfer from the forming tool to the sheet should not be ignored, especially for material with relatively low electrical resistance. The heat generation principle in electric hot-assisted ISF can be modified as Eq. (3).

$$Q_{E\_actural} = I^2 \left(R_{contact} t_t + k R_{tool} t_T \right), \tag{3}$$

where $Q_{E\_actural}$ is the thermal energy generated in the local forming area, R_{tool} is the contact resistance of the forming tool, k is the coefficient of heat conduction and t_T is the total forming time. It should be noted that t_T is much greater than t_t. It can be seen that materials owning large resistances are suitable for electric hot-assisted ISF because of easier heat creation. For some materials with low resistances, it is possible to take the advantage of heat transferred from the forming tool to elevate the temperature at the local forming area.

3. Experimental tests

In this work, both frictional stir- and electric hot- assisted ISF are conducted on a three axis CNC milling machine with a maximum spindle rotation speed of 6000 rpm. Fig. 1 shows the established setups for both processes. The sheet of 180 mm × 180 mm dimension was clamped by a dedicated clamping fixture. The forming forces throughout the process were measured by a JR3 6-axis load cell mounted below the fixture. In addition, an infrared camera with working range of -40 to 2000 °C and resolution of 0.1 °C was used to monitor the temperature variation during the hot ISF process. Compared to the conventional ISF process, no additional apparatus is required in frictional stir-assisted ISF. The essential difference of frictional stir-assisted ISF is the employment of a very high tool rotation speed. For electric hot-assisted ISF, a DC power source, an appropriate electrode connection, and insulating components, are all employed in the developed system. Tool rotation is usually not allowed in electric hot-assisted ISF in order to guarantee a stable contact between the forming tool and assembled electrode.

In this study the process capabilities, such as processing efficiency and heating rate, of frictional stir- and electric hot- assisted ISF, were investigated by forming magnesium alloy AZ31B with 1.4 mm sheet thickness into a truncated funnel (Fig. 2a). A helical toolpath with an incremental depth of 0.5mm was used. ROCOL® copper based anti-seize compound was also used to ensure better lubrication and conductivity between the forming tool and the blank sheet in electric hot-assisted ISF. To make the results comparable, this lubricant was also adopted in frictional stir-assisted ISF.

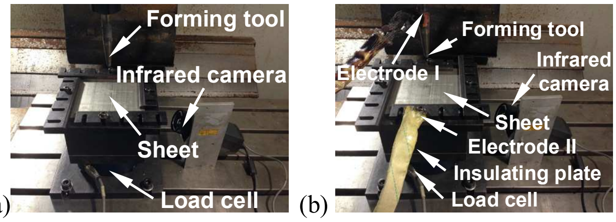


Fig. 1. Experimental setups: (a) frictional stir-assisted ISF and (b) electric hot-assisted ISF.

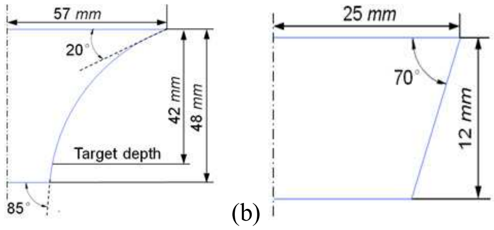


Fig. 2. Experimental parts dimensions: (a) truncated funnel and (b) cone with steep wall angle.

4. Results and Discussion

In this section, a comparison of process capabilities for frictional stir- and electric hot- assisted ISF is presented in detail. A preliminary investigation about the formability of AZ31B using the conventional ISF was first carried out. The fracture depth and the corresponding maximum formable wall angle for AZ31B were about 7.50 mm and 36.28°, respectively. Its maximum achievable depth of 42 mm was set as the target for both frictional stir- and electric hot- assisted ISF for forming AZ31B.

4.1. Processing efficiency

In forming AZ31B, in order to evaluate process efficiency, the feed rate is gradually increased from 800 mm/min until the truncated funnel could not be successfully produced. In frictional stir-assisted ISF, the tool rotation speed was constant at 5000 rpm. The supplied current in electric hot-assisted ISF was 500A. Fig. 3 shows processing efficiency of frictional stir- and electric hot- assisted ISF. Successfully formed samples as well as failed ones, are shown in Fig. 4. It can be confirmed that both techniques were capable of significantly improving the formability of AZ31B and successfully forming the truncated funnels with the desired depth, when the feed rate of the tool was 800 mm/min. When the feed rate speeded up to 1200 mm/min, the truncated funnel could still be successfully achieved in both processes. However, when the feed rate was increased to 1600 mm/min, the component fractured at the depth of about 35 mm in electric hot-assisted ISF, while there was no fracture observed in the frictional stir-assisted ISF process. It was experimentally found that the maximum feed rate for the frictional stir-assisted ISF is 2000 mm/min. Although the processing efficiency of both techniques may be improved with an increase of tool rotation speed and current, the obtained results indicate that frictional stir-assisted ISF with tool rotation speed of 5000 rpm is superior to electric hot-assisted ISF with current of 500 A in terms of the processing efficiency, as higher feed rates can be employed without fracture in the frictional stir-assisted ISF process.

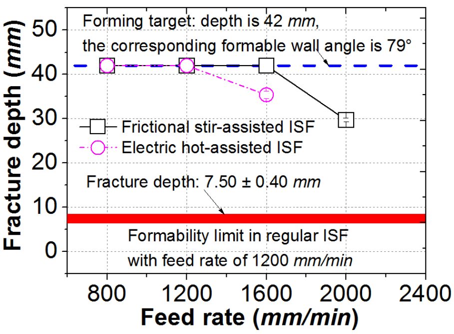


Fig. 3. Processing efficiency of frictional stir- and electric hot- assisted ISF in forming AZ31B.

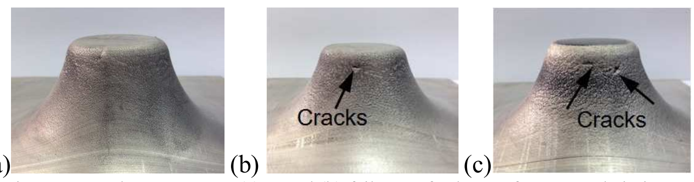
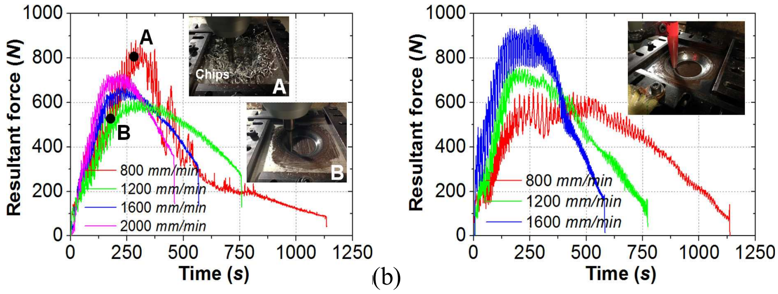


Fig. 4. Formed components: (a) sound (b) failure at feed rate of 2000 mm/min in frictional stir-assisted ISF and (c) failure at feed rate of 1600 mm/min in electric hot-assisted ISF.

4.2. Variations of forming force and temperature

Fig. 5 shows the measured resultant forming forces. In frictional stir-assisted ISF (Fig. 5a), an abnormal oscillation of resultant force was observed at the tool feed rate of 800 mm/min. This is because the forming process coupled with milling process when an inappropriate combination of tool rotation speed and feed rate is selected. Although the component shape can be successfully formed, the milling effect can be observed, which significantly reduces sheet thickness. The generated parts at tool rotation speed of 5000 rpm and feed rate of 800 mm/min are shown in Fig. 5a. After the feed rate increased to 1200 mm/min, no obvious chips can be observed. Additionally, the resultant force increases with the increase of feed rate in general. As shown in Fig. 5b, the resultant force measured in electric hot-assisted ISF also increases with the increase of feed rate. No chips were detected in the whole process because tool rotation was inactive. Without considering the case accompanied by the milling effect, the measured resultant forces in electric hot-assisted ISF are larger than the ones obtained in frictional stir-assisted ISF at the same feed rate. This phenomenon may attribute to the competition between increased friction on the tool-workpiece interface and material softening under elevated temperature conditions.

The temperature variations were measured by an infrared camera as shown in Fig. 6. In frictional stir-assisted ISF, the observed milling effect results in a great temperature fluctuation at the depth of 7.5 to 17.5 mm. Different feed rates of the forming tool will not obviously affect the increasing rate of temperature, which confirms the analytical observation as given in Section 2.1. Moreover, it is found that the temperature elevated by frictional heat tends to be saturated after a certain depth due to the achievement of thermal equilibrium. In electric hot-assisted ISF, the temperature increasing trends are also not sensitive to the change of feed rate. As compared to frictional heat, the heating rate of Joule heat is much faster than that of frictional heat. Another difference between these two techniques is that no thermal equilibrium is reached in electric hot-assisted ISF.



(a) (b)

Fig. 5. Resultant force measured in: (a) frictional stir-assisted ISF and (b) electric hot-assisted ISF.

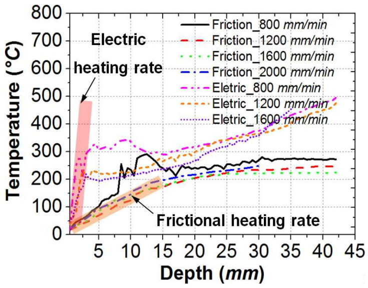


Fig. 6. Comparison of temperature increase in frictional stir- and electric hot-assisted ISF.

4.3. Forming of a truncated cone with steep wall angle

As demonstrated in Section 4.1, it is possible to form AZ31B into a geometrical shape with a 79° wall angle at the feed rate of 1200 mm/min in frictional stir- and electric hot- assisted ISF. A shallow cone shape with a steep wall angle of 70° was designed as illustrated in Fig.2b to examine the process adaptability under extreme conditions. The results suggested that electric hot-assisted ISF can successfully form this shape while the frictional stir-assisted ISF fails to do so. One explanation is that the lower heating rate in the frictional stir-assisted ISF process cannot lift the temperature up to the required level at the initial stage, but becomes too high at the final stage due to the milling effect (Fig. 7a). Another reason is that the milling effect significantly decreases the sheet thickness of the inclined wall, which reduces the load carrying capacity of the part, gradually causes deformation instability and ultimately results in material failure. This can be confirmed by the force variation history as shown in Fig. 7b, in which the forming force reduced after 100s. In electric hot-assisted ISF, the local forming temperature is immediately heated up, and no abnormal phenomenon can affect the forming process.

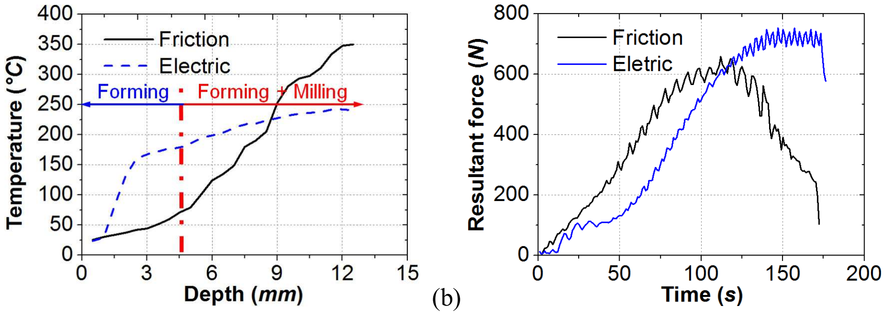


Fig. 7. Forming of cone with steep wall angle: (a) temperature trends and (b) resultant forces.

5. Conclusion

In this paper, frictional stir- and electric hot- assisted ISF are compared in detail. The important findings are outlined as follows:

(1) As compared to electric hot-assisted ISF with current of 500 A, frictional stir-assisted ISF with tool rotation of 5000 rpm can successfully form the truncated funnel shape at a higher feed rate. According to current experimental results, it may be concluded that frictional stir-assisted ISF has higher processing efficiency than electric hot-assisted ISF.

(2) The heating rate in electric hot-assisted ISF is much faster than that of frictional stir-assisted ISF. This characteristic guarantees the feasibility to quickly bring the forming temperature to required levels.

(3) Inappropriate combination of tool rotation speed and feed rate changes the forming process to a milling process, which acts as an obstacle to the other advantages of frictional stir-assisted ISF.

(4) Electric hot-assisted ISF is more suitable than frictional stir-assisted ISF in forming components with the feature of a steep wall angle.

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