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Surface characterization of heat-affected zone in robot-based increment sheet forming

Nazarul Abidin Ismail [1,2*], Mohd Idris Shah Ismail [1], Mohd Khairol Anuar Mohd Ariffin [1], Azizan As'arry [1]

[1] Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, MALAYSIA.
[2] Industrial Automation Control Section, Electrical Engineering Department, German Malaysian Institute, Jalan Ilmiah, Taman Universiti, 43000 Kajang, Selangor, MALAYSIA.
*Corresponding author: nazarul@gmi.edu.my

KEYWORDS

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ABSTRACT

Robot-based incremental sheet forming is a new prospect in processing sheet metal due to the flexibility of robotic arm for fabricating a product with complex shape. Since the heat-affected zone on forming tool has a direct contact with the workpiece surface, the formed surface topography contains much information concerning the forming condition. In this study, the heat-affected zone on forming tool in robot-based incremental sheet forming of aluminum alloy sheet was analyzed using surface characterization. The experiments were conducted by evaluating the generation of heat-affected zone on the forming tool under different forming shapes, robot speeds, wall angles and step sizes. The energy dispersive spectrometry was used to analyze the elemental distribution on the surface of forming tool. The results indicated that the frictional heating and size of contact interface between surfaces of forming tool and workpiece have significantly affected the dimension of heat-affected zone on forming tool. It is also found that the adhesion material of aluminum revealed at the region of heat-affected zone on forming tool. These findings are important to identify the tool condition and forming performance in product manufacturing.

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1.0 INTRODUCTION

Incremental sheet forming (ISF) process is a modern approach for fabrication of sheet metals by the step-by-step of forming tool to the workpiece without the need of dies or molds, which costs in term of time and money. This process is performed by a forming tool that forms the sheet in a series of localized incremental deformations. ISF has been used for various materials including aluminum alloys (Al-Ghamdi and Hussain, 2015, Durante et al., 2011), steels (Jeswiet and Young, 2005; Li et al., 2017), magnesium alloys (Leonhardt et al., 2018), titanium (Uheida et al., 2017; Khazaali and Fereshteh-Saniee, 2016) and polymer (Shubhamkar, 2016; Sabater et al., 2018). However, aluminum alloys are receiving more attention from researchers for conducting research. Nimbalkar and Nandedkar (2013) analyzed the current status of incremental sheet metal forming in terms of types of ISF, equipment used in ISF, tool path generation and comparison between robot forming with conventional forming methods.

A new incremental bending method has been proposed by Li et al. (2016) for complicated curved sheet metal which design mainly including three degree-of-freedom working tables, supporting and the punching system, control system, and a 3D scanning system. However, this method still utilizes additional supporting and punching system to form complex shapes. Pandivelan and Jeevanatham, (2015) noted the formability evaluation of AA6061 aluminum alloy sheets on single point incremental forming (SPIF) using a CNC vertical milling machine. It concluded that the formability decreases as the step depth increase during the SPIF. Since the CNC machine is rigid and easier to control, it still needs improvement towards complex product shapes. ISF process with an industrial robot can be an innovative and feasible method to comply with complex products. Due to the dynamic working range of industrial robots, the ability of the robot based ISF process to create a larger and complex workpiece can be enhanced.

The friction applies locally external heat has been proven to improve the ductility of sheet metals and enhance formability using ISF (Shubhamkar, 2016). Zhaobing, (2018) analyzed the development of heat-assisted ISF (HA-ISF) such as laser heat, friction heat, and electric heat. It noted that the friction in HA-ISF is easy to be implemented, but two major challenges are uncontrollable forming temperature and severe tool wear. The wear of forming tools and metal sheets could be kept at a relatively low level when the forming temperature is properly controlled (Meier et al., 2013). Increasing spindle speed and tool diameter influence in friction and temperature resulting in lower force values (Sabater et al., 2018). Gupta and Jeswiet (2017) stated that the effect of increasing feed rate and tool rotational speed on temperature for the aluminum alloy of AA 5754-H32. The observation was conducted by a flat tool to form a variable wall angle geometry and the temperature was recorded using an infrared camera. It concluded that increasing temperature could reduce the force needed to form the materials.

Many researchers have improvised on the ISF technology, which focusing on processing parameters and their influences (Bagundach et al., 2013; Lu, 2016, Arfa et al., 2013), wall thickness distributions (Li et al., 2012; Mohammadi et al., 2016; Lu et al., 2016), springback effect (Abeyrathna et al., 2017; Araghi et al., 2009), formability (Pandivelan and Jeevanatham, 2015; MacAnulty et al., 2016, Liu et al., 2013) and surface quality (Li et al., 2013; Mugendiran et al., 2014) but less on the heat-affected zone (HAZ) that affected to the forming tool. Since the frictional force of ISF process between forming tool and workpiece generates heat, the HAZ on forming tool has a direct effect on the formed workpiece surface and the surface topography of forming tool contains much information relating to the forming condition. In this present work, the HAZ on forming tools in the robot based ISF process of AA3003 aluminum alloy was experimentally investigated. The experiments were conducted by evaluating the generation of heat-affected zone on the forming tool under different forming shapes, robot speeds, wall angles, and step sizes. The energy dispersive spectrometry also was used to analyze the elemental distribution on the surface of the forming tool.

2.0 EXPERIMENTAL WORK

In this study, the AA3003 aluminum alloy sheet with 0.5 mm thickness was used as the workpiece. The forming tool with a hemi-spherical tip of a 10mm in diameter was fabricated from AISI D2 tool steel. The chemical composition of the workpiece and forming tool are shown in Table 1. Figure 1(a) shows the experimental setup for incremental sheet forming using a six-degree-of-freedom industrial robot. The forming tool was held by a standard collet tool holder that attached to the robot head. The robot has great movement capability and suitable for performing a continuous path-controlled movement. The continuous-path movement of the robot was guided using robot teach pendant, in which the sequence of forming points was defined to the robot in teach mode. The blank workpiece was fixed vertically on the worktable. The tool path used was a helical tool path and the experiments has been conducted to perform the required shape profiles of a truncated pyramid and truncated cone as shown in Figure 1(b) and 1(c), respectively, with a depth of 30 mm. The truncated pyramid cone profile has 200 mm x 200 mm top square, while the truncated cone profile has 200 mm in outer diameter.

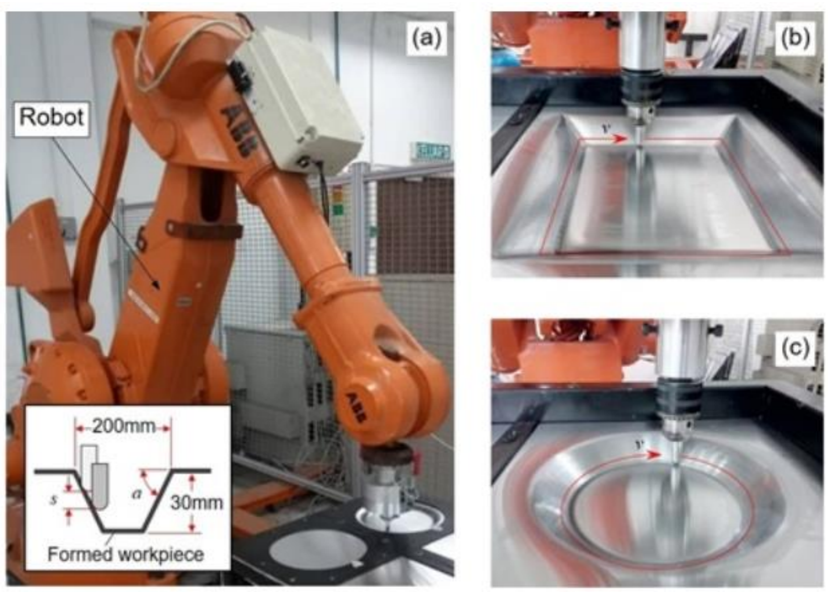

Figure 1: Experimental set-up and tools.

Table 1: Chemical composition of the workpiece.

Material	Elements
AA3003	Si (0.60); Mn (1.5); Fe (0.70); Cu (0.20); Mg (0.05); Zn (0.10); Al (Bal.)
AISI D2	C (1.55); Si (0.30); Mn (0.35); Cr (12.00); Mo (0.75); V (0.90); Fe (Bal.)

Three processing parameters considered in this study are robot speed (v), step size (s) and wall angle (a). Robot speed is referred to as feed rate, while the step size is the vertical movement of the tool. However, the final shape of the truncated pyramid and cone differs in the wall angle, as the wall angle is a manipulated parameter. Wall angle was manipulated by controlling the step of the tool along the length or width, and radius of the truncated pyramid and cone, respectively. For example, on a truncated cone profile, a 45-degree wall angle for a 0.3 mm step size is achieved by moving the tool by 0.3 mm along the radius before the tool moves vertically by 0.3 mm. After the robot based ISF process, the forming tool was cleaned using an ultrasonic cleaner machine for the observation and measurement of HAZ by a digital microscope that integrated with the measurement system as shown in Figure 2. The area of HAZ, AHAZ (in mm2) could be calculated using Equation (1) (Weisstein, 2019; Harris and Stocker, 1998).

$$A_{\mathrm{HAZ}} = 2\pi r h \tag{1}$$

Where r is the radius of forming tool and h is the dome height of HAZ on forming tool. Furthermore, to analyze the element containing on the forming tool surface, the energy dispersive spectrometry (EDS) was utilized.

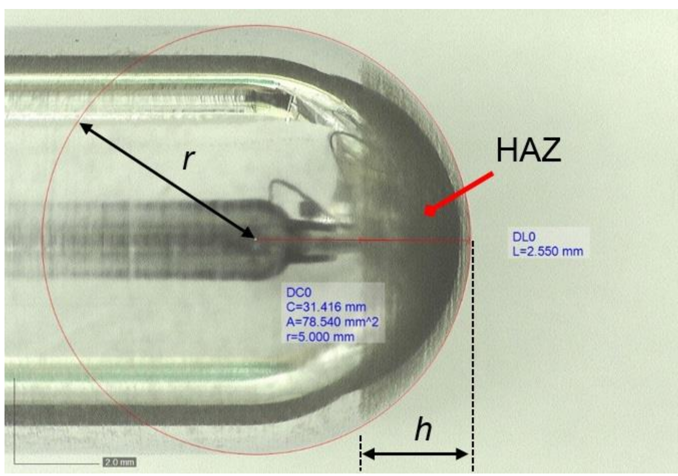

Figure 2: Forming tools under observation.

3.0 RESULTS AND DISCUSSION

The HAZ on forming tool is a zone that directly contacts the workpiece during ISF process. Figure 3 shows the HAZ pattern generated on the forming tool after the robot based ISF process under constant 50 mm/s robot speed, 0.5 mm step size and 45° wall angle. It can be seen clearly the HAZ pattern on forming tool for truncated pyramid profile has a fan shape, while the HAZ pattern for truncated cone profile showing a circular shape. This is due to the tool path trajectory for truncated pyramid profile is square manner, which the forming tool contacts unevenly with the workpiece, i.e. since there are four ribs separating the planar faces on truncated pyramid profile, only specific areas of forming tool are contacted to workpiece surface in the straight path. In contrast to the truncated cone profile, the forming tool and workpiece are contacted uniformly in curved path to form the circular shape of HAZ. From this result, the next discussion is focused only on the workpiece with truncated cone profile.

To investigate the effects of processing parameters on HAZ for producing truncated cone profile, the robot speed of 150 mm/s and 250 mm/s, step size of 0.3 mm and 0.5 mm, and wall angle of 45° and 60° were used. Based on the results from Figure 4, it reveals that the area of HAZ under 45° wall angle is greatly smaller compared to the 60° wall angle. This result confirms the workpiece with a higher angle of tapered wall possess larger contact interface between forming tool and workpiece (Fritzen et al., 2013; Otsu et al., 2014). In addition, the step size also plays a significant factor that influences the area of HAZ. It can be seen from Figure 4; the higher 0.5 mm step size generates a larger area of HAZ due to the large incremental step down compared to the 0.3 mm step size. This large incremental step down also leads to having a larger contact interface between forming tool and workpiece and also obtained by Li et al., (2014, 2015). For the effect of robot speed, the faster movement of forming tool resulted in the larger area of HAZ as illustrated in Figure 4. It can be stated that the robot speed or relative sliding velocity has a positive linear relationship with frictional heating (Uheida et al., 2018), in which the robot speed has a marginal impact on the heat generated at the contact interface.

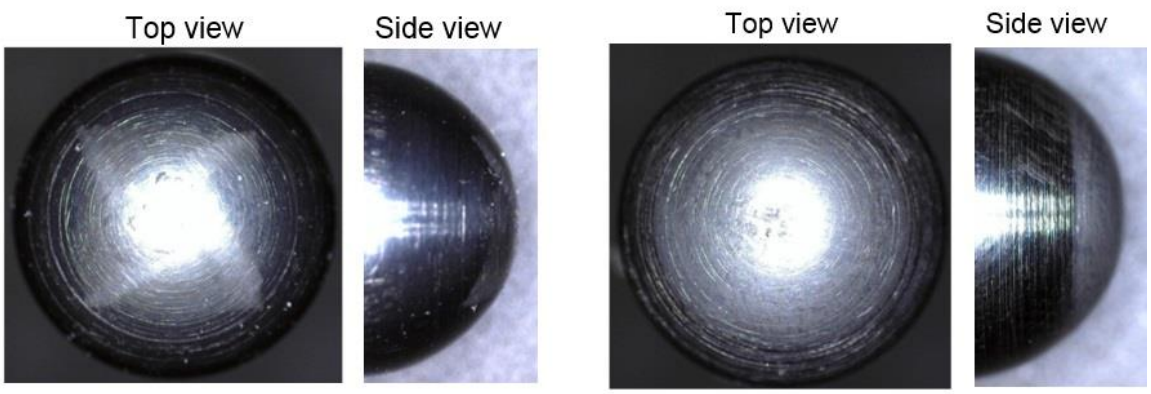

Figure 3: The HAZ pattern generated on the forming tool after the robot based ISF process.

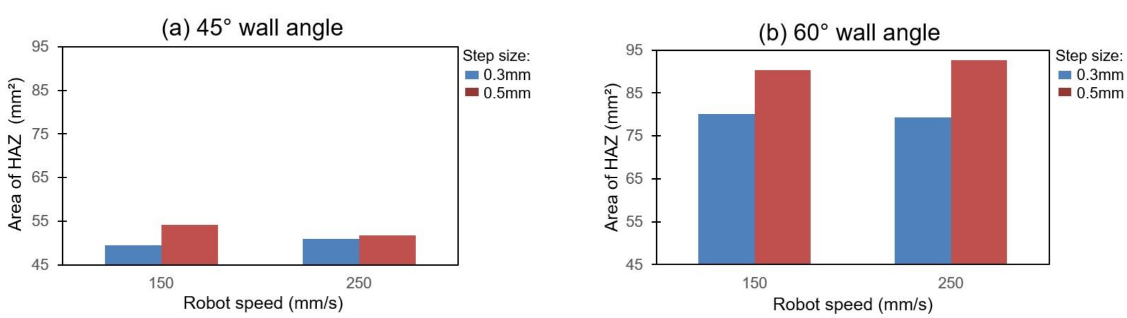

Figure 4: Effects of processing parameters on HAZ for producing truncated cone profile.

An EDS analysis was carried to identify the elemental composition of the intermetallic particles at the surface of forming tool after 100 runs under 150 mm/s robot speed, 0.3 mm step size and

45° wall angle. Figure 5 shows the SEM images and EDS analysis with three main elements detected at HAZ and non-HAZ of forming tools. It can be seen that the element of oxygen (O) is higher three times at HAZ compared to non-HAZ, which caused by oxidation as a reaction of frictional heating between the forming tool and workpiece interface (Hutchings, 2017). It can be indicated that the presence of deposited elements of aluminum (Al) from the workpiece. This result confirms the material transfers from the workpiece to the forming tool and as an evidence of the adhesive wear on the forming tool (Kato, 2002). At the HAZ also reveals the reduction of chromium (Cr) and manganese (Mn) elements, since it has been replaced by the elements of O and Al.

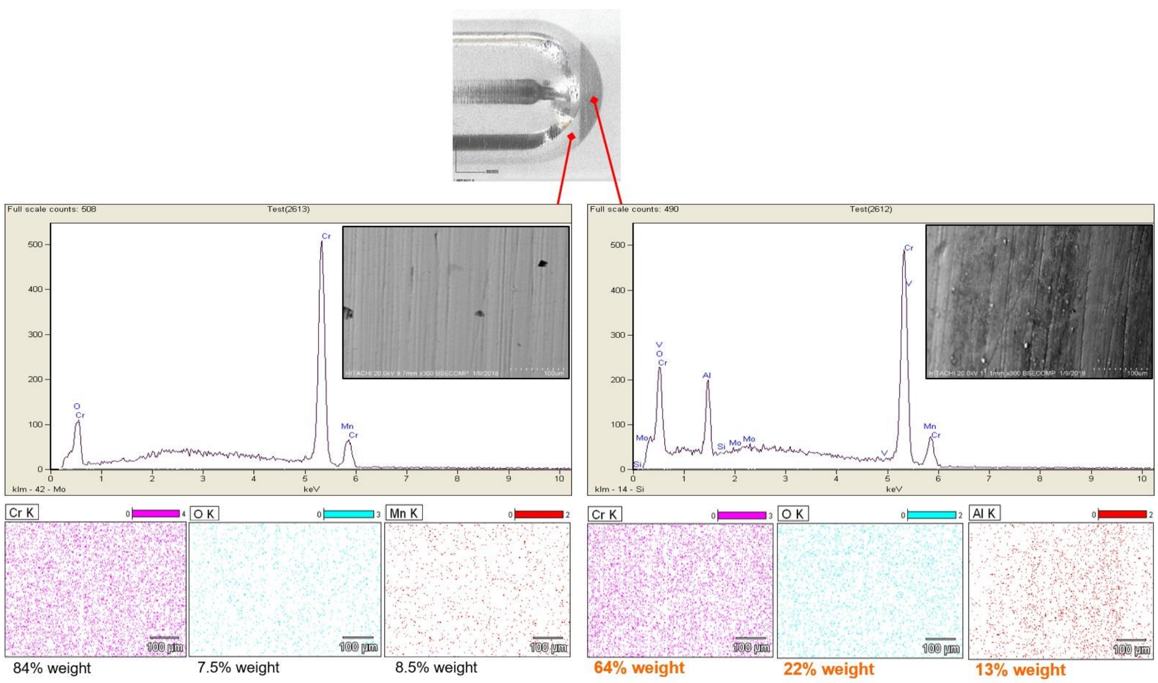

Figure 5: The SEM images and EDS analysis with three main elements detected at HAZ and non-HAZ of forming tools.

4.0 CONCLUSION

The surface characterization of heat-affected zone (HAZ) on forming tool in robot-based incremental sheet forming (ISF) of aluminum alloy was experimentally investigated. The ISF process with curved path could cause the forming tool uniformly contacted to workpiece compared than straight path. The processing parameters of wall angle and step size are significantly affected on HAZ due to the size of contact interface between forming tool and workpiece, while robot speed has a marginal impact on the heat generated at the contact interface. The oxidation layer on HAZ occurred from a reaction of frictional heating and the adhesion material of aluminum from the workpiece revealed at HAZ of forming tool. For further research, these findings can be used in pattern recognition of tool condition to monitor the tool wear for minimizing the process cost and control the product quality consistently.

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