Experimental Formability Study of Ti6Al4V Sheet Metal using Friction Stir Heat Assisted Single Point Incremental Forming Process

V. D. Golakiya*, M. K. Chudasama

*Mechanical Engineering Department, Dr S & S Ghandhy Government Engineering College Surat, Gujarat Technology University, Gujarat, India
#Mechanical Engineering Department, Government Engineering College Surat, Gujarat Technology University-395001, Gujarat, India

1. INTRODUCTION

Single point incremental forming (SPIF) process is a novel sheet metal forming process. SPIF process is characterized with higher flexibility, lower tooling cost and reduces lead time due to die-less sheet metal forming process [1]. It is more suitable for rapid prototypes and small - medium scale production of sheet metal parts, which needs no special type of tooling and has low initial cost as compared to conventional stamping forming process [2]. The blank sheets metals are localized incrementally deformed using a simple hemispherical end forming tool, whose path is specified in a CNC machining center or robot. SPIF process has higher formability because of mode of deformation of sheet under stretching and shearing action [3]. Due to great formability at room temperature, the SPIF method is extensively used for the aluminum and steel alloy sheet material. However, the process has limited to industrialize because of lower surface quality, uniform thickness, geometrical accuracy and higher forming time of formed parts [4].

The uses of lightweight material such as titanium alloy components have continuously increased in the important fields such as aeronautical, automotive and biomedical field due to economic, environmental and biomedical compatible in nature. These alloy materials have good mechanical properties such as high strength to weight ratio, toughness, wear resistance fatigue behavior and corrosion resistance compared to other materials such as aluminum and steel alloys [5]. Among the titanium alloys, the Ti6Al4V is used 80% of total titanium alloy in the USA [6]. However, the Ti6Al4V titanium sheet is difficult to form at room temperature because of they possess low uniform elongation, resistance to deformation, high springback and yield to tensile ratio (high hardness and poor formability). So, they are commonly formed with low-speed forming at elevated temperature of 750~950 °C [7]. Lightweight materials such as AA2024-T3, AZ31 B-O, AA6061-T6,
AA6063 and titanium alloys and high strength alloy such as MnB5, DP 980 and DC04 steel alloy have possessed a poor formability at room temperature. In order to form these alloys, heat assisted incremental sheet forming (ISF) techniques are more suitable with minimum tooling cost and lower lead time at higher temperature such as laser heat assisted, electrical heat assisted, induction heat assisted friction stir heat assisted processes [8].

In the past two decades, many researchers and academicians have carried out experiments to analyze the forming of lightweight sheet materials using different types of the heat assisted ISF techniques. Duflou et al. [9] have formed cone shape specimens of Ti6Al4V with laser heat assisted technique of ISF with local dynamic heating. The results showed that cone shape specimens were formed with lower forming force and higher dimension accuracy. Ambrogio et al. [10] studied the influence of process parameters such as tool diameter, step size, feed rate and lubrication on the formability of magnesium alloy AZ31B at the room temperature and in warm condition. The formability of AZ31B was observed higher in warm conditions as compared to room temperature. Further, complex design of heating equipment is creating difficulties while carried out the forming of sheet. Fan et al. [11] developed a new technique to heat the sheet metal based on electric current. In this technique, the localized heat is generated at tool-sheet interference by DC power supply. They investigated maximum formable angle and part accuracy. Ambrogio et al. [10] suggested a range of deformation rates of high-strength titanium alloys pass into a state of increased ductility without loss of strength properties by using additional force impulse loading, and the implementation of dynamic non-equilibrium processes. Grün et al. [19] investigated the behavior of Ti6Al4V sheet formability with friction stir SPIF process technique. The result showed that medium tool rotation of 2000 rpm speed lead to lower the rate of tool wear, improved the formability and reduce the forming forces.

To the best of author’s knowledge, experimental investigation of process parameters on forming of Ti6Al4V sheet metal without use of heating equipment in single point incremental process is not reported so far. Because of wide use of Ti6Al4V titanium alloy in the field of biomedical, aeronautics and automotive, friction stir heat assisted single point incremental forming of Ti6Al4V sheet has been investigated in this study. In order to evaluate the formability of sheet metal part in SPIF process, the parameters like speed, feed, step size and wall angle were selected.

2. PRINCIPLE AND EQUIPMENT OF EXPERIMENTAL SETUP

Figure 1 shows the principle experimental set up employed in present work. The experimental set up consist of basic elements such as sheet blank, forming tool, vice, fixture and a CNC vertical machining center. The 3-axis CNC Machine (Jyoti PX20 with Siemens controller) with a maximum working space of 510 x 510 x 510 mm³ and 400 kg load capacity of table is used for experimental work.

The tool is made of tungsten carbide (WC) material with a 10 mm diameter hemispherical-end; it is selected due to its high hardness, heat resistance and wear resistance. The blank sheet is firmly clamped with clamping screws in the fixture. A tool with hemispherical shape is forming the blank sheet incrementally in to desired shape. The Ti6Al4V alloy, a hard-to-form lightweight alloy sheets has been selected for experimental tests. Its chemical constituents (as-received condition) are Ti-87.49 % Al-6.8 %, V-4.8,
H–0.015 %, Fe–0.3, O–0.2%, Si–0.15%, C–0.1 %, N–0.05 and others–0.4 % in mass percentage. Titanium is an allotropic substance consisting of a cubic structure (α-Ti) and a compact hexagonal structure up to a temperature of 882°C (β-Ti). The truncated cone-specimens were formed from 98 x 98 mm² blank size sheets having a thickness of 1 mm. All test samples of sheet have been cut from annealed 1-mm-thick Ti6Al4V alloy sheets by water jet machining process. Before each experiment, OKS200 MoS2 paste lubricant was applied on top surface of blank sheet, which prevent the oxidation of the specimen surface at higher temperature during forming process (Figure 2).

The truncated cone geometries with constant angle is formed with 46 mm top base diameter and vertical depth of 18 mm. The truncated cone was employed to determine the SPIF formability of Ti6Al4V. The desired tool path to form the truncated cone specimen was generated using Microsoft Excel Software. All truncated specimens with constant angle have been formed using Z-level tool path. In Z-level tool path, first tool moves in XY-plane, reaches its starting point, then tool takes a step in the vertically (z-axis) downward with specified step size. This motion of tool continues till the complete specimen is formed. Figure 3 shows the CAD truncated cone specimen model with tool path.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The plan of experiments with process parameters are summarized in Table 1. In present study, there are four variables parameters such as speed, feed, step size and wall angle. The formability is one of the important response parameter of sheet metal forming process. Formability of sheet material in SPIF process is represented in different approach such as fracture forming limit, maximum formable angle and maximum forming depth.

In present work, maximum forming depth of specimen is measured as a formability of Ti6Al4V sheet material, which can be measured just before specimen part fractured during forming process. All specimens are formed till either design depth of 18 mm or the fractured of specimen during forming process. After the fractured the specimens are unloaded from the fixture and depth of fractured specimens are reported as the Z-axis co-ordinate on computer screen of the machine. The experimentation was carried out to investigate influence of various parameters such as speed, feed, step size and wall angle on formability.

3.1 Influence of Wall Angle

The conical frustums specimens with diameter of 46 mm at the top and wall angle of 55°, 50°, and 45° are selected to evaluate the formability in the friction stir heat assisted SPIF process of Ti-6Al-4V alloy. The plan of experiments and the experiment results are shown in Table 1.
TABLE 1. Plan of experimental work and result

(a) Formability test results by varying the speed and step size with constant wall angle

| Exp. No. | Wall angle (α)-degree | Speed (s)-rpm | Feed (f)-mm/min | step-size (z)-mm | Depth of formed part (d)-mm |
|----------|------------------------|---------------|-----------------|-----------------|----------------------------|
| 1        | 55                     | 700           | 1000            | 0.25            | 6                          |
| 2        | 55                     | 1000          | 1000            | 0.1             | 5.5                        |
| 3        | 55                     | 1400          | 800             | 0.25            | 6.25                       |

(b) Formability test results of wall angle

| Exp. No. | Wall angle(α)-degree | Depth of formed part (d)-mm | Constant parameters |
|----------|-----------------------|-------------------------------|---------------------|
| 3        | 55                    | 6.25                          | speed 1400 rpm,     |
|          |                       |                               | feed 800 m/min,    |
|          |                       |                               | tool diameter 10    |
|          |                       |                               | mm and step size    |
|          |                       |                               | 0.25mm.             |
| 4        | 50                    | 7.25                          |                     |
| 5        | 45                    | 18                            |                     |

(c) Formability test results of speed

| Exp. No. | Speed(s)-rpm | Depth of formed part (d)-mm | Constant parameters |
|----------|--------------|-----------------------------|---------------------|
| 6        | 700          | 7.50                         | wall angle 45°,     |
|          |              |                              | speed 1400 rpm,    |
|          |              |                              | feed 800 m/min,    |
|          |              |                              | tool diameter 10    |
|          |              |                              | mm and step size    |
|          |              |                              | 0.25mm.             |
| 7        | 1000         | 10.25                        |                     |
| 5        | 1400         | 18                           |                     |

(d) Formability test results of feed

| Exp. No. | Feed (f)-mm/min | Depth of formed part (d)-mm | Constant parameters |
|----------|-----------------|-----------------------------|---------------------|
| 5        | 800             | 18                          | wall angle 45°,     |
| 8        | 1000            | 6.25                        | speed 1400 rpm,    |
|          |                 |                              | tool diameter 10    |
|          |                 |                              | mm and step size    |
|          |                 |                              | 0.25mm.             |
| 9        | 1200            | 5.5                         |                     |

(f) Formability test results of step size with varying wall angle

| Exp. No. | Step size (z)-mm | Wall angle (α)-degree | Depth of formed part (d)-mm | Constant parameters |
|----------|------------------|----------------------|-----------------------------|---------------------|
| 4        | 0.25             | 50°                  | 7.25                        |                     |
| 10       | 0.1              | 50°                  | 7.25                        | speed 1400 rpm and  |
|          |                  |                      |                             | tool diameter 10   |
|          |                  |                      |                             | mm.                 |
| 5        | 0.25             | 45°                  | 18                          |                     |
| 11       | 0.1              | 45°                  | 18                          |                     |

In the first set of three specimens as shown in Table 1(a) with wall angle of 55° was formed with varying the speed and step size. All three specimens had early failed with poor surface finish as shown in Figure 4. It shows that wall angle is the most significant parameter for formability. In the second set of three specimens as shown in Table 1(b) with wall angle of 55°, 50° and 45° have been formed with considering other parameters as constant. As can be seen from the results and as shown in Figure 5, the specimen with wall angle of 45° has successfully formed at a depth of 18 mm and wall angle with 50° and 55° had early failed at a depth of 7.52 and 5.25 mm, respectively. The result showed that forming depth decreases with an increase in the wall angle as shown in Figure 6(a). The sheet metal had more stretching at higher wall angle, hence thinning of sheet metal increases with an increase in the value of wall angle based on cosine law.

3.2. Influence of Speed

In the third set of three experiments plan with varying the speed as shown in Table 1(c), the specimens have formed with varying the speed and keep other parameters constant. The specimen formed successfully at forming depth of 18 mm with speed of 1400 rpm but specimens are failed at depth of 7.5 mm and 10.25 mm at lower
3. 3. Influence of Feed In the fourth set of three experiments plan with varying the feed as shown in Table 1(d), the specimen have been formed with varying the feed of 800, 1000, and 1200 mm/min with keeping other parameters constant. Figure 8(a) shows that specimen with feed of 800 mm/min was successfully formed but the specimens with feed of 1000 and 1200 mm/min had failed at depth of 6.25 and 5.5 mm, respectively as shown in Figure 8(b, c). Further, as shown in Figure 6(c) depth of forming specimens had increased with decreased in the value of feed.

At the lower feed, the more heat generated at interface between tool and work-piece due to slower rolling of the tooltip over the contact surface and rate of the heat dissipated is very slow. The metal is becoming ductile in nature and more straining occurred because of increasing the temperature at forming zone. Hence, the formability of sheet metal is increased. For higher feed, the formability decreased due to lower heat generation at tool interface, faster the tool tip rolls over the contact surface.

3. 4. Influence of Step Size In the fifth set of three experiments plan, the influence of step size with varying wall angle as shown in Table 1(f). As can be seen from results, the specimens had formed without any crack at 45° wall angle in two 0.1 and 0.25 step sizes as shown in Figure 9(c, d).

---

3. 3. Influence of Feed

In the fourth set of three experiments plan with varying the feed as shown in Table 1(d), the specimens have been formed with varying the feed of 800, 1000, and 1200 mm/min with keeping other parameters constant. Figure 8(a) shows that specimen with feed of 800 mm/min was successfully formed but the specimens with feed of 1000 and 1200 mm/min had failed at depth of 6.25 and 5.5 mm, respectively as shown in Figure 8(b, c). Further, as shown in Figure 6(c) depth of forming specimens had increased with decreased in the value of feed.

At the lower feed, the more heat generated at interface between tool and work-piece due to slower rolling of the tooltip over the contact surface and rate of the heat dissipated is very slow. The metal is becoming ductile in nature and more straining occurred because of increasing the temperature at forming zone. Hence, the formability of sheet metal is increased. For higher feed, the formability decreased due to lower heat generation at tool interface, faster the tool tip rolls over the contact surface.

3. 4. Influence of Step Size

In the fifth set of three experiments plan, the influence of step size with varying wall angle as shown in Table 1(f). As can be seen from results, the specimens had formed without any crack at 45° wall angle in two 0.1 and 0.25 step sizes as shown in Figure 9(c, d).

---

speed of 700 and 1000 rpm, respectively as shown in Figure 7. It seems that forming depth is increases with an increase in tool rotation speed as shown in Figure 6(b) because of thermal softening effect at tool-sheet interface. At the low rotations speed of 700 and 1000 rpm, the range of temperatures were lower at tool interface 60 to 90 °C observed by Infrared non-contact temperature measurement gun, as shown in Figure 2(a). At such low temperature, insufficient heat generated in the forming zone resulted in reduced formability of the part. In SPIF process, friction heat generation at tool-sheet interface is directly proportional to tool rotation speed [20].
On the other hand, the specimens with wall angle of 55° early failed at depth of 7.25 mm as shown in Figure 9 (a, b). This shows that wall angle is more significant parameter than step size and, there is no significant effect is found on formability with varying the step size of 0.1 mm and 0.25 mm.

4. CONCLUSIONS

In this study, experimental investigation of single point friction stir incremental forming process of Ti-6Al-4V is performed. The results of the study can be summarized as follows:

- Process parameters, such as wall angle, speed and feed have influence on the formability of sheet metal blank. Formability is increased with a decrease in the wall angle from 55° to 45° and the highest formability is obtained in term of maximum forming depth of 18 mm at wall angle of 45° due to lower the stretching of material. It has been found that the wall angle has significant influence on the formability of sheet metal.

- With an increase in the speed from 700 to 1400 rpm, the formability of sheet metal is increasing of 7.5 mm to 18 mm in term of maximum forming depth. The sheet metal shows higher formability at higher temperature cause of higher rubbing action at contact surface due to increases speed. While formability decreases from 18 mm to 5.5 mm in term of forming depth as the feed increasing from 800 to 1200 mm/min. At higher feed rate, formability is lower due to poor accumulation of heat at contact surface, causes more rate of heat dissipated.

- Furthermore, step size of 0.1 and 0.25 mm did not have any significant effect on formability.

- The most influencing parameters in this process are wall angle followed by tool rotation speed and feed. So with correct combination of these parameters, it can come up to safe forming of the Ti6Al4V blank sheet without additional heat assisted equipment.

In this approach, the present study helps to user to get recommendations about, parameters with their range should be select to form the hard to form material of Ti-6Al-4V by friction stir SPIF process at room temperature.

5. REFERENCES

1. Arfa, H., Bahloud, R. and BelHadjSalah, H.J.I.j.o.m.f., "Finite element modelling and experimental investigation of single point incremental forming process of aluminum sheets: Influence of process parameters on punch force monitoring and on mechanical and geometrical quality of parts", *International Journal of Material Forming*, Vol. 6, No. 4, (2013), 483-510, doi: 10.1007/s12289-012-1101-z
2. Vahdani, M., Mirnia, M.J., Bakhshi-Jooybari, M. and Gorji, H.J.T.I.J.o.A.M.T., "Electric hot incremental sheet forming of ti-6al-4v titanium, aa6061 aluminum, and dc01 steel sheets", *International Journal of Advanced Manufacturing Technology*, Vol. 103, No. 1-4, (2019), 1199-1209, doi: 10.1007/s00170-019-03624-2
3. Jackson, K. and Allwood, J.J.J.o.m.p.t., "The mechanics of incremental sheet forming", *Journal of Materials Processing Technology*, Vol. 209, No. 3, (2009), 1158-1174, doi: 10.1016/j.jmatprotec.2008.03.025
4. Mohanraj, R. and Elangovan, S.J.T.o.i.C.S.F.M.E., "Incremental sheet metal forming of ti-6al-4v alloy for aerospace application", *Transactions of the Canadian Society for Mechanical Engineering*, Vol. 44, No. 1, (2019), 56-64, doi: 10.1139/tesme-2018-0276
5. Ambrogio, G., Filice, L., Gagliardi, F.J.M. and Design, "Formability of lightweight alloys by hot incremental sheet forming", *Materials & Design*, Vol. 34, (2012), 501-508, doi: 10.1016/j.matdes.2011.08.024
6. Eylon, D. and Seagle, S.J.S.P., "Titanium’99: Science and technology", Vol., No., (2000), 866-875.
7. Lee, H.-S., Yoon, J.-H., Park, C.H., Ko, Y.G., Shin, D.H. and Lee, C.S.J.J.o.M.P.T., "A study on diffusion bonding of superplastic ti–6al–4v alloy grade", *Journal of Materials Processing Technology*, Vol. 187,(2007), 526-529, doi: 10.1016/j.jmatprotec.2006.11.215
8. Liu, Z.J.T.I.J.o.A.M.T., "Heat-assisted incremental sheet forming: A state-of-the-art review", *The International Journal of Advanced Manufacturing Technology*, Vol. 98, No. 9, (2018), 2987-3003, doi: 10.1007/s00170-018-2470-3
9. Duflou, J., Callebaut, B., Verbert, J. and De Baerdemaecker, H.J.C.a., "Laser assisted incremental forming: Formability and accuracy improvement", *CIRP Annals*, Vol. 56, No. 1, (2007), 273-276, doi: 10.1016/j.cirp.2007.05.063
10. Ambrogio, G., Filice, L. and Manco, G.J.C.a., "Warm incremental forming of magnesium alloy az31", *CIRP Annals*, Vol. 57, No. 1, (2008), 257-260, doi: 10.1016/j.cirp.2008.03.066
11. Fan, G., Gao, L., Hussain, G., Wu, Z.J.I.J.o.M. T. and Manufacture, "Electric hot incremental forming: A novel technique", *International Journal of Machine Tools and Manufacture*, Vol. 48, No. 15, (2008), 1688-1692, doi: 10.1016/j.ijmachtods.2008.07.010
12. Fan, G., Fengtao Sun, Meng, X., Lin Gao and Tong, G., "Electric hot incremental forming of ti-6al-4v titanium sheet", *The International Journal of Advanced Manufacturing Technology*, Vol. 49, No. 9-12, (2010), 941-947, doi: 10.1007/s00170-009-2472-2
13. Rahman, F., Seyedkashi, S. and Hashemi, S.J.I.I.o.E., "Experimental study on warm incremental tube forming of aa6063 aluminum tubes", *International Journal of Engineering, Transactions C: Aspects*, Vol. 33, No. 9, (2020), 1773-1779, doi: 10.5829/ije.2020.33.09c.11
14. Xu, D., Lu, B., Cao, T., Zhang, H., Chen, J., Long, H., Cao, J.J.M. and Design, "Enhancement of process capabilities in electrically-assisted double sided incremental forming", *Materials & Design*, Vol. 92, (2016), 268-280, doi: 10.1016/j.matdes.2015.12.009
15. Buffa, G., Campanella, D. and Fratini, L.J.T.I.J.o.A.M.T., "On the improvement of material formability in spif operation through tool stirring action", *The International Journal of Advanced Manufacturing Technology*, Vol. 66, No. 9-12, (2013), 1343-1351, doi: 10.1007/s00170-012-4412-9

16. Otsu, M., Katayama, Y. and Muranaka, T., "Effect of difference of tool rotation direction on forming limit in friction stir incremental forming", in *Key Engineering Materials*, Trans Tech Publ. Vol. 622, (2014), 390-397.

17. Ambrogio, G. and Gagliardi, F.J.T.I.J.o.A.M.T., "Temperature variation during high speed incremental forming on different lightweight alloys", *The International Journal of Advanced Manufacturing Technology*, Vol. 76, No. 9-12, (2015), 1819-1825, doi: 10.1007/s00170-014-6398-y

18. Chausov, M., Pylypenko, A., Berezin, V., Volyanska, K., Maruschak, P., Hutsalyuk, V., Markshova, L., Nedoseka, S. and Menou, A.J.T., "Influence of dynamic non-equilibrium processes on strength and plasticity of materials of transportation systems", *Transport*, Vol. 33, No. 1, (2018), 231-241, doi: 10.3846/16484142.2017.1301571301549.

19. Grün, P., Uheida, E., Lachmann, L., Dimitrov, D. and Oosthuizen, G.J.T.I.J.o.A.M.T., "Formability of titanium alloy sheets by friction stir incremental forming", *The International Journal of Advanced Manufacturing Technology*, Vol. 99, No. 5, (2018) 1993-2003, doi: 10.1007/s00170-018-2541