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Development of Novel Tools for Electric Heating Assisted Incremental Sheet Forming

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Abstract

The electricity assisted incremental sheet forming (E-ISF) is a new flexible forming method, which could further widen the application of the incremental sheet forming (ISF) process on conventional 'hard-to-form' materials such as titanium alloy Ti6Al4V. However, in the E-ISF process, challenges remain in the rough surface finish of formed parts and severe tool wear. To overcome this problem, various novel tools have been designed for the improvement of surface quality in this paper. To validate the designed tools, experiments were conducted on hot ISF of Ti6Al4V sheets with an initial thickness of 1 mm. By comparing the tool temperature and the surface finish, different tools were evaluated. The result suggests that by introducing a design for water cooling, tool wear can be reduced whilst the surface finish can be improved by employing a roller ball at the tool tip.

Key words: Electric heating assisted incremental forming, tools, surface finish

1. Introduction

Incremental sheet forming (ISF) is a competitive manufacturing route for flexible and rapid forming of complex sheet metal products. Comparing to traditional sheet forming processes such as stamping, it could form parts without the use of specific dies and forming press, which would enable significant reduction of both manufacturing cost and lead time as well as energy consumption. This process is a particularly suitable for producing small batched, customized products that can be used in automotive, aerospace and, biomedical sectors.

In recent years, lightweight alloys have been increasingly used for applications in such as automotive industry where both high performance and high energy efficiency are critical considerations. However, the lightweight alloys are usually the so-called “hard-to-form” materials with poor ductility at room temperature. Although the ISF process could potentially increase the formability, manufacturing of lightweight alloys such as Ti6Al4V by using ISF is still a challenge. By increasing the forming temperature, the hot ISF approach can be a possible solution. In recent years, a variety of heat-assisted ISF techniques were conducted to improve the ISF performance. Various methods of heat generation in ISF have been reported including by using hot air blowers [1], conduction with a forming chamber [2], radiation by a laser beam [3-6], friction through tool rotation [7-9] or Joule heat by DC current [10-14].These technologies greatly enhanced the ISF capabilities in fabrication of lightweight alloys. Comparing with all reported methods as mentioned above, the ISF process assisted by electric heating shows more economical benefits than the other methods. This method is easy to implement, efficient in heating, independent of part geometry and easy to control temperature.

Although the electric heating assisted ISF approach shows better performance during ISF process in terms of force reduction, accuracy improvement, and formability enhancement, the surface quality obtained was not always satisfactory. This may be due to the chemical reaction induced by excessive heating, such as oxidation and severe surface scratches due to poor friction condition at tool-sheet interface under high temperature conditions. In addition, long processing time under high-temperature conditions would also cause severe tools wear, which causes an even worse sheet surface quality. Furthermore, the poor surface finish and defects cause weak spots on the sheet, which may result in an early fracture of components. Thus sheet surface finish is an important consideration in developing hot ISF process for both sufficient surface quality and mechanical performance.

Concerning surface quality improvement in hot ISF, a possible solution is to improve the lubrication. Fan et al [11] employed an self-lubricating Ni disulfide metal matrix composite to form Ti6Al4V sheet. Zhang et al [15] found that the Nano-K2Ti4O9 whisker enhanced solid graphite lubrication and the solid graphite/MoS2 powder-based porous ceramic coating could provide an excellent lubrication condition in ISF processing of AZ31 sheet. In both cases, good surface quality of the formed parts was obtained. However, the coating approach may require complex pre-forming processing, which can be both time consuming and expensive.

Another possible approach is to improve the forming tool design to reduce the friction. In the conventional ISF process, rigid tool with hemispherical head is employed. The tool may be made of various materials e.g. tungsten carbide [3, 4, 10-12], die steel [5, 6], high speed steel [7, 13], H13 hot work steel [8], air-hardened D2 [9] and BOHLER K100 tool steel [14]. In some cases, wear-resistant or friction - reduction coating may be applied to the tool tip [3-6]. However, the friction between tool and sheet is sliding friction, which may inevitably cause scratches on the sheet surface under hot condition.

In this paper, novel forming tools were developed and investigated to improve the surface finish in the E-ISF process. Different forming tools including a conventional rigid tool, a water cooled rigid tool, a roller-ball tool and a roller-wheel tool were developed and tested. Experiments were conducted for hot forming of Ti6Al4V sheets with the effect of the surface finish evaluated by using different tools. The results suggested that by cooling down the tools and employing the rolling tool head design, tool wear can be reduced and the surface finish can be improved.

2. Development of Hot Forming Tools

Ti6Al4V is a challenging sheet material to be used in E-ISF processing. This titanium alloy has high strength-to-density ratio and corrosion resistance. However, the formability of Ti6Al4V is poor at room temperature. According to previous studies, when the forming temperature is over 500ºC, the plasticity of Ti6Al4V can be improved and the yield stress reduced r to about 50% [16]. Concerning the E-ISF of Ti6Al4V, Fan et al [11] suggested that a temperature range of 500~600ºC is suitable for Ti6Al4V to be formed with higher workability. In the E-ISF process, to maintain the working temperatures on the sheet, electric current continuously passes through the tool, which results in considerable amount of accumulated heat to cause a high tool temperature. The high working temperature may cause tool oxidation and tool wear [10, 11] and this leads to lowered surface quality and scratches [5]. To reduce the tool temperature, tool oxidation and improve the sheet surface quality, three major approaches were employed in this work:

1) Employment of high temperature alloy: other than the steel, high temperature nickel alloy GH4169 was employed in the tool design and development. In this way, the tool oxidation may be minimized.

2) Water cooled tool design: cooling channel is designed in the tool for reduced tool temperature by the water cooling approach.

3) Employment of rolling tool tip: other than sliding friction condition from the rigid tool, roller ball or roller wheel is designed at the tool tip to improve the friction condition.

Based on these three major approaches, four different tools, including the rigid tool, the water cooled tool, the roller-ball tool and the roller-wheel tool were developed in this work as described in the following.

3.1 Rigid tool

During the E-ISF process, heat will generate on the tip of the forming tool when the electric current passes through the tool-sheet interface. To minimize the tool oxidization, nickel alloy GH4169 is utilized to produce the forming tool. As shown in

Fig. 1, a rigid tool tip is designed which is similar to conventional design while the only change is from the tool material. This tool is considered as a benchmark comparing to other developed tools.

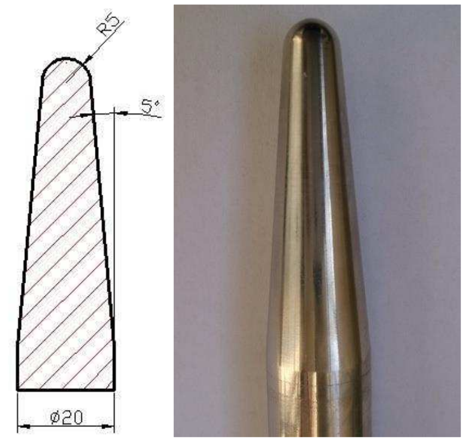


Fig. 1 Rigid tool and CAD model

2.2 Water cooled rigid tool

To prevent over-heating of the tool due to the accumulated heat, a water cooled tool was designed as shown in Fig. 2. In this tool, stepped bores are drilled to form a cooling channel. In this way, the accumulated heat can be taken away by the circulation of water driven by a pump. The tool material is GH4169 nickel alloy. Using this design, the tool temperature is expected to be reduced in the E-ISF process.

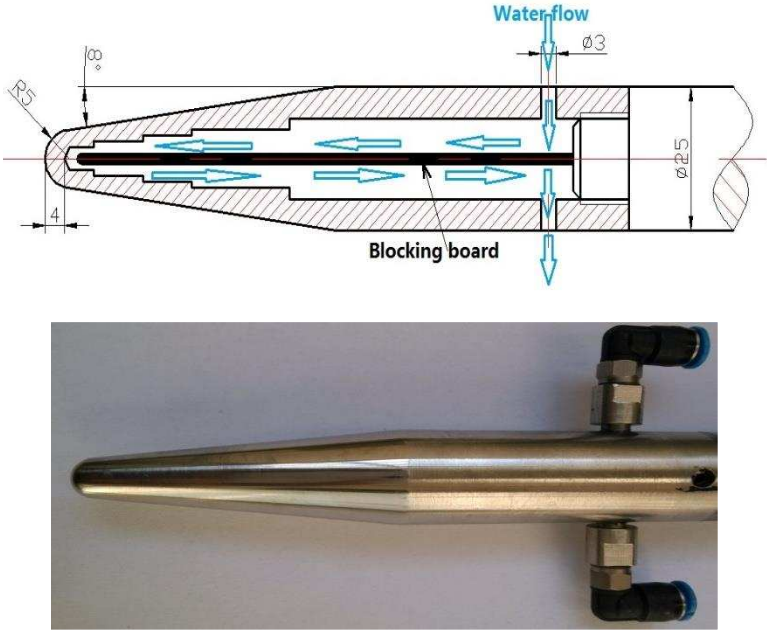


Fig. 2 Water cooling tool and CAD model

2.3 *Roller-ball tool*

The principle of roller-ball tool was proposed by Kim and Park [17]. Lu et al [18] further investigated the friction effect of the roller-ball tool. These works suggested that the roller-ball tool was able to improve surface quality at room temperature by changing friction condition from sliding into rolling. In this work, the conventional roller-ball tool is redesigned for the hot work conditions. As shown in Fig. 3, comparing to conventional roller-ball tool, a water channel is designed in the tool to reduce the tool temperature. The water flows out of the tool through a small hole at the ball cap. In this way, the temperature of roller ball can also be reduced. With the water cooling, the heat expansion can be minimized to ensure the smooth rolling of the ball. In addition, while the tool is made from steel, the roller-ball is made by nickel alloy to reduce the possible oxidation on the ball surface.

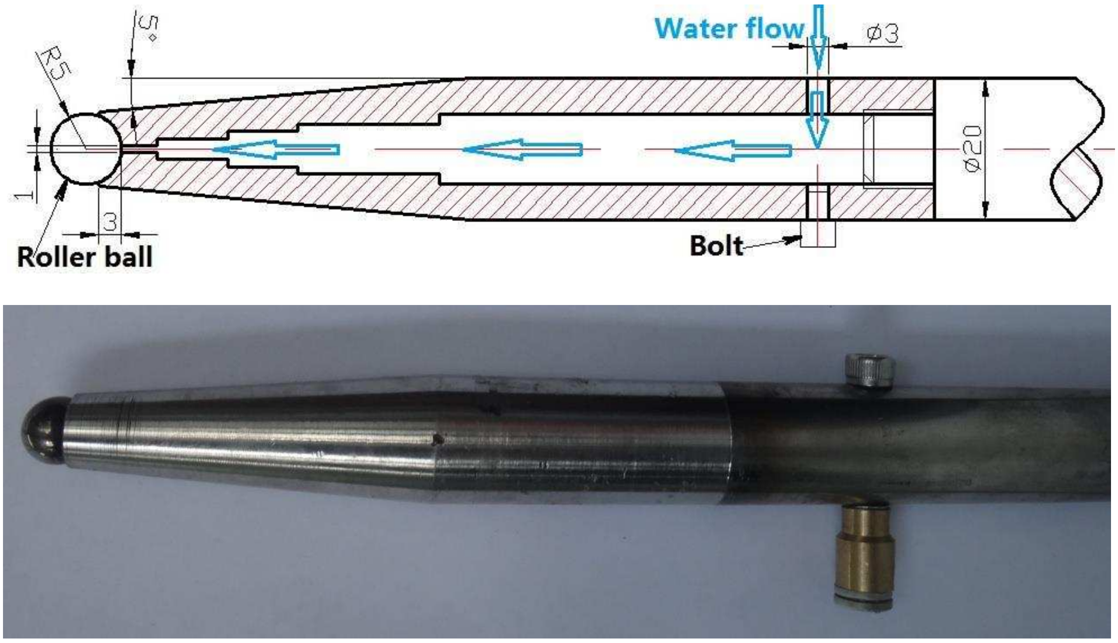


Fig. 3 Roller-ball tool and CAD model

2.4 *Roller-wheel tool*

In this work, another tool design to avoid sliding condition is the roller-wheel tool. As shown in Fig. 4, other than a hemispherical head, a roller wheel is placed at the tool end. The water was pumped into the tool through a ring and come out of the tool through small holes in the wheel holder. In this way, the water in the tool will spray out onto the wheel to reduce the wheel temperature. The wheel is made of the GH4169 alloy to minimize the possible oxidization.

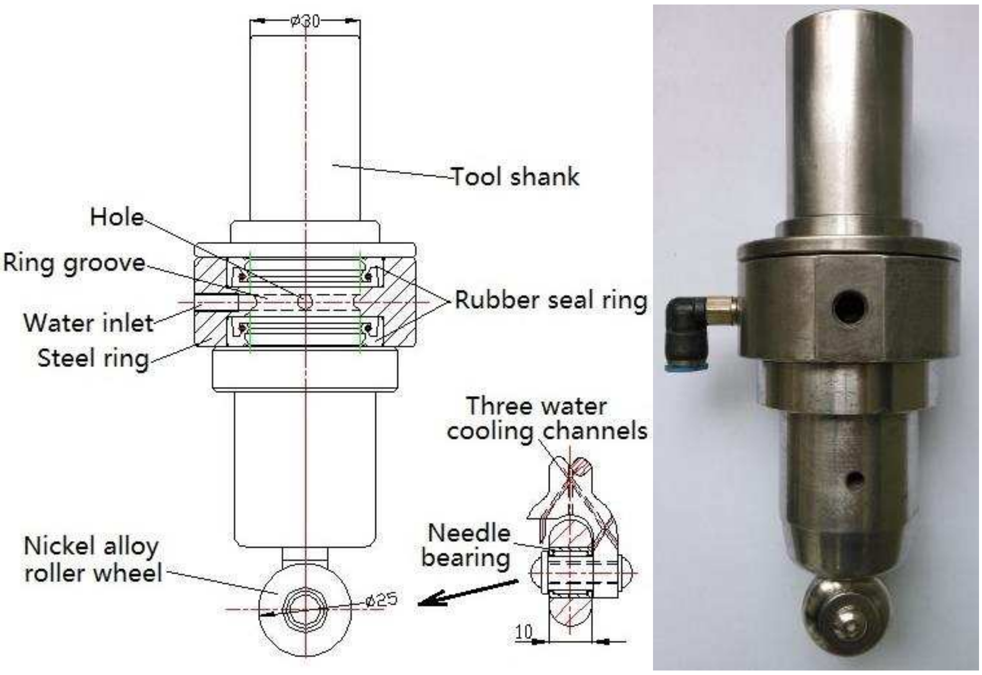


Fig. 4 Roller-wheel tool and CAD model

In the E-ISF process, rather than the roller-ball tool, the wheel could only rotate in one direction. To keep the wheel rolling direction pointing to the tool moving direction, the tool is rotated by a servo motor controlled spindle on the ISF machine according to the prepared NC program.

3. The E-ISF machine and experimental setup

Among the various heating assisted techniques proposed by researchers, electric hot incremental sheet forming(E-ISF) was adopted in this study by employing the developed tools in this study. A horizontal ISF machine was employed as shown in Fig. 5. The forming tool moves in the X, Y, Z directions driven by the machine to incrementally deform the sheet. A thermal cameral is placed at the other side of sheet to measure the forming temperature.

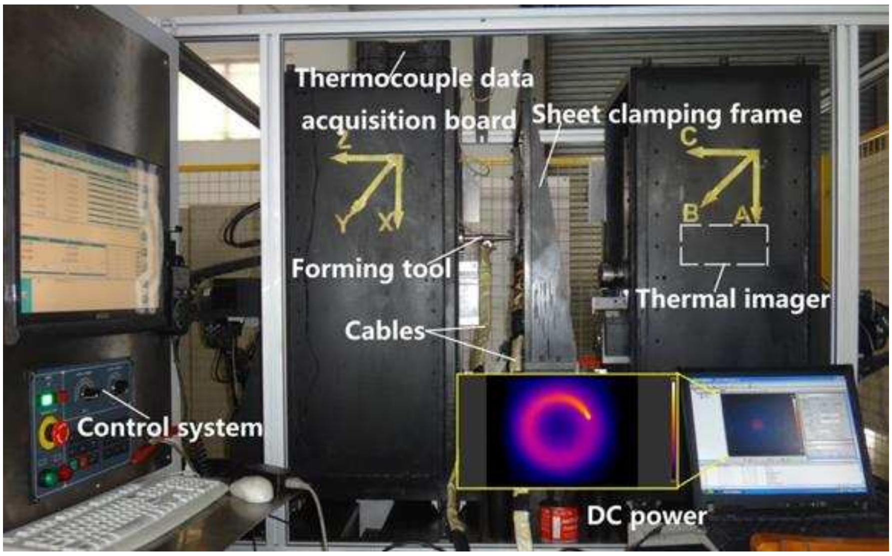


Fig. 5 Experimental setup of E-ISF system

Concerning the electric heating method, a DC power with maximum current of 800A was employed and connected to the tool and the sheet clamp. The DC current flows through the forming tool, the sheet blank and the clamp to constitute a closed circuit. In this circuit, most of the heat is generated at the tool-sheet contact zone as the resistance of that area is much larger than the rest of the closed circuit.

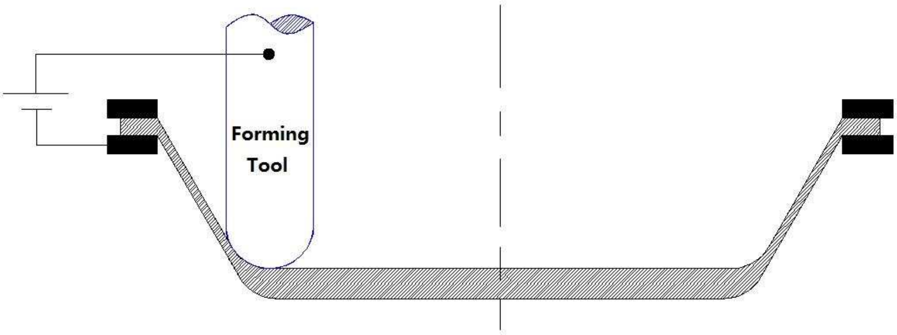


Fig. 6 Schematic of circuit connection in E-ISF

In all the experiments, 1.0 mm thick Ti6Al4V sheet with size 180×180mm^2 were chosen to form a truncated cone with an initial outer diameter of 90mm, a depth of 20mm, and a wall angle of 45°, as shown in Fig. 7. A spiral toolpath with a constant incremental step size of 0.3mm was applied in the E-ISF process. The feed rate was fixed as 800*mm/min*. ROCOL copper based anti-seize compound was used to ensure both good lubrication and conductivity between forming tool and sheet blank. With the assistance of a thermal camera, the dynamic local forming temperature was maintained at about 500~600ºC by adjusting proper current input.

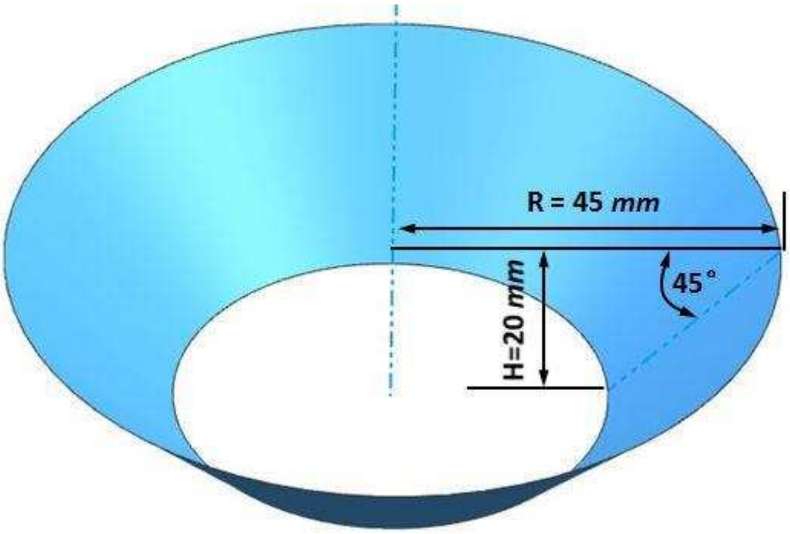
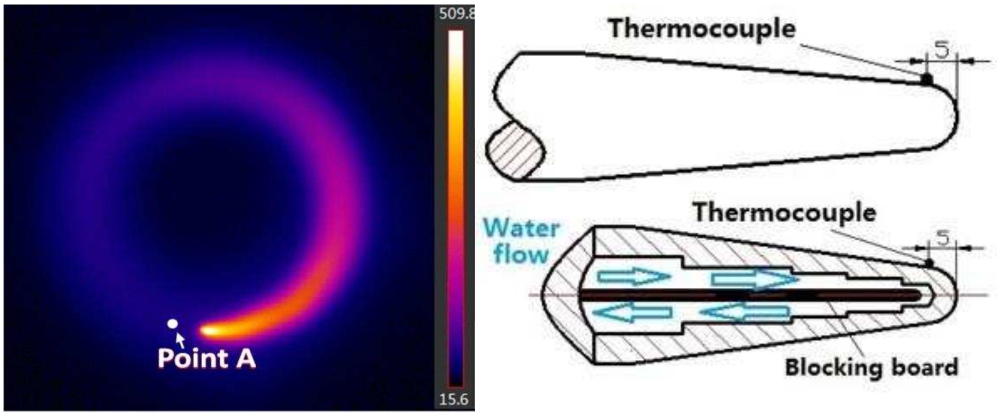


Fig. 7 Designed 45° truncated cone for the investigation of surface quality

In the experiment, the four developed tools are employed. A water pump with a water tank is used to form a water circuit for the tools with water cooling design. In the E-ISF process, forming temperature is a key parameter that affects the final quality of the sheet part. In this work, three temperatures including the maximum temperature on the sheet, the temperature evolution on a particular point on the sheet and the tool temperature were investigated. As shown in Fig. 8(a), the thermal camera was employed to measure the sheet temperature. Note that the sheet temperature is measured at the back of sheet, which may be lower than that at the tool-sheet contact side. Concerning the measurement of tool temperature, thermal couples were placed on both the rigid tool and the water cooled tool to measure the tool temperature as shown in Fig. 8(b). However, for the roller-ball tool and the roller-wheel tool, the tool temperature was not measured. This is because the water comes out from the tool tip and spray on the thermal couple, which cause inaccurate temperature date in the experiments.



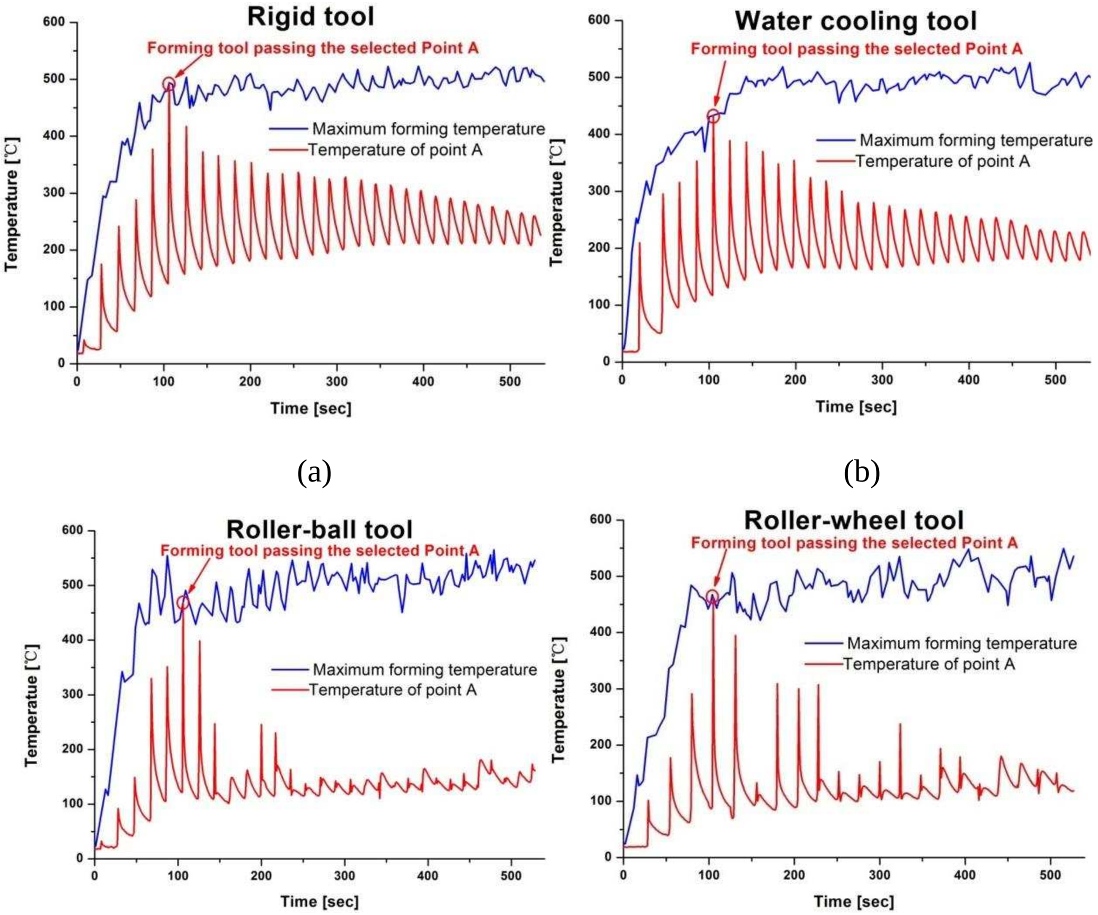
(a) (b)

Fig. 8 Temperature measurement

4. Experimental results

4.1 Forming temperature

The evolution of maximum forming temperature and the temperature at point A are given in Fig. 9. As can be seen in the figure, during the ISF process, the maximum forming temperature on the sheet gradually increases to the target temperature of 500ºC and maintains at that level for all cases. Concerning the local temperature at point A, cyclic heating can be observed as the measured temperature oscillates: when the tool approaches the region where the point A locates, the temperature at the point periodically reaches its maximum value in every tool pass. When the tool moves away to a next location after the temperature achieves its peak value, the maximum temperature in the cycle could fall to a lower value. Comparing the rigid tool and the water cooling tool, similar trend of temperature variation can be observed at the point A. Comparing the rolling type tool with the rigid type tool, the variation of temperature becomes less obvious when the tool left the point A. This may be due to the different tool design: for both the roller-ball tool and the roller-wheel tool, the cooling water comes out of the tool other than recycling back to the water tank. The water was spray on the sheet which further cooled the sheet temperature down and reduced the cyclic heating effect.



(a) (b)

(c) (d)

Fig. 9 Comparison of maximum sheet temperature: (a)Rigid tool; (b) Water cooling tool; (c) Roller ball; (d) Roller wheel

The variations of temperature for the rigid tool and the water cooled tool can be observed as shown in Fig. 10. Without water cooling, the temperature of the rigid tool increases rapidly in the first 100 seconds. After the initial stage, the temperature keeps increasing gradually and it is approaching 600ºC at the final stage. Concerning the water cooled tool, in the first 100 seconds, the temperature increases to about 100º C. After that, temperature became stabilized until the end of forming. This result suggested that with the water cooling system, the temperature could be effectively controlled at a lower level.

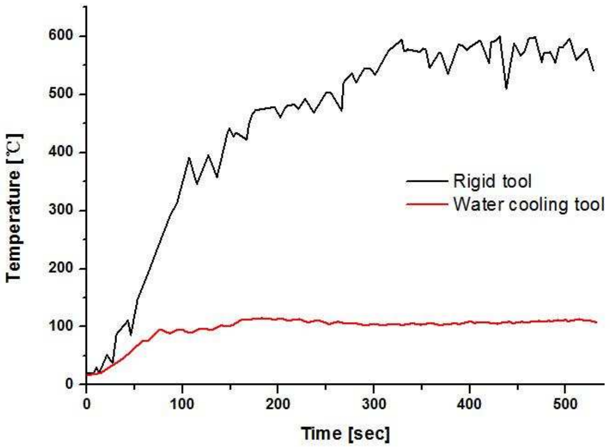


Fig. 10 Comparison of tool temperature

4.2 Tool wear

Tool wear is another challenge in the conventional E-ISF process. After the forming experiment, the tool tips were examined as shown in Fig. 11. As can be seen in the figure, severe tool wear can be observed from the rigid tool. This is due to the high working temperature of the tool. For water cooled rigid tool, the tool wear on tool tip is less severe than the case without water cooling. The cooling design and the lowered working temperature protected the tool tip from wear. Concerning the roller-ball tool, as can be seen in Fig. 11(c), shining surface can be observed, which suggests negligible tool wear on this surface. For the roller-wheel tool, some wear marks on the wheel surface can be observed. This is because, other than the roller-ball, the wheel can only rotate in one direction. The wheel may be stuck in the forming process and this may cause some stains on the wheel surface.

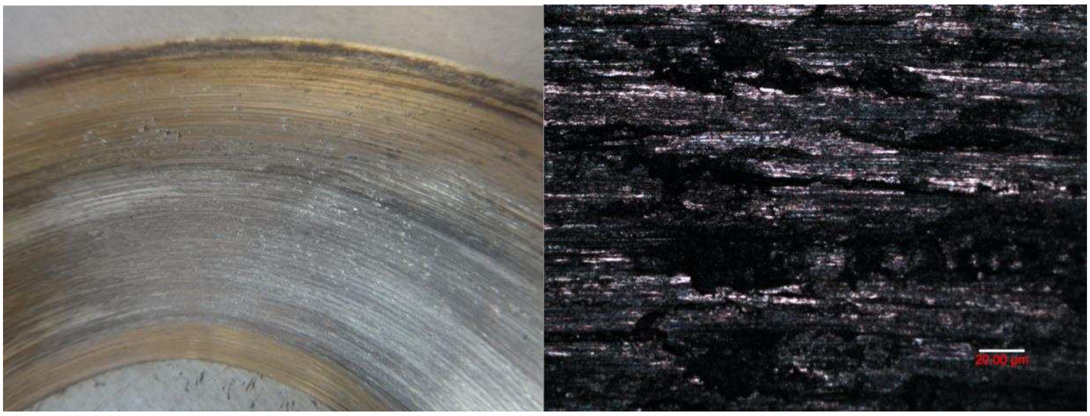
(a) **(b)**

(c) **(d)**

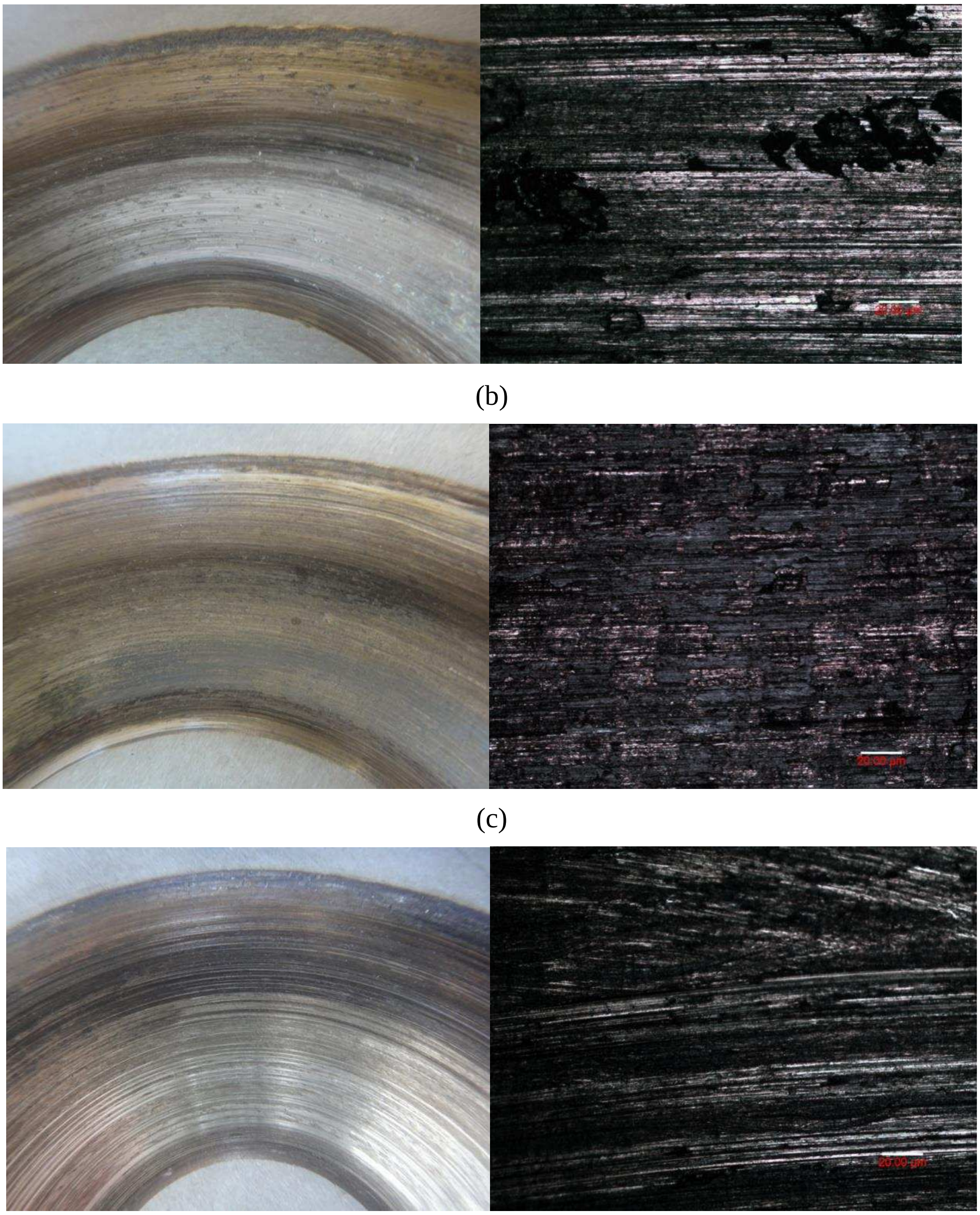
Fig.11 Wear on tool tips: (a) Rigid tool (b) Water cooling tool (c) Roller ball (d) Roller wheel

4.3 Surface finish of E-ISF parts

The surface finishes of the parts generated by different tool were examined as shown in Fig. 12. As can be seen in the Fig. 12(a) and (b), for the parts generated by using the rigid tool with or without water cooling, obvious scratches and small defects can be observed. These small defects may be caused by the electric discharge. Comparing Fig. 12(a) and (b), it can be found that with the water cooling and reduced wear, the number of small cavities is reduced. Concerning the roller-ball tool, good surface finish can be observed without obvious defects on the surface. For the roller-wheel tool, scratches can be observed without small defects comparing to the case of water cooled tool in Fig. 12(b). It can be concluded that the high temperature and tool wear are the main causes of small defects on the surface. By employing the rolling tools with rolling friction, the defects and scratches can be minimized.



(a)



(b)

(c)

(d)

Fig. 12 Surfaces of the truncated cones formed by different tools:

(a) Rigid tool (b)Water cooling tool (c)Roller-ball tool (d)Roller-wheel tool

In order to obtain a further understanding of the difference between surface qualities obtained, surface roughness of truncated cones formed by different tools were measured as shown in Fig. 13 and Table 1. As can be seen in the figure, the worst surface finish comes from the rigid tool with a maximum Rz value of 17.2μm. The best result is obtained from the roller-ball tool with a maximum Rz value of 4.6μm. Concerning the case of water cooled tool, although the tool wear can be reduced, the scratch on the sheet surface is still obvious. The surface finish from the roller-wheel tool is worse than the case of the roller-ball tool, but because of the rolling friction condition, the surface finish is still better than both cases of the rigid tools.

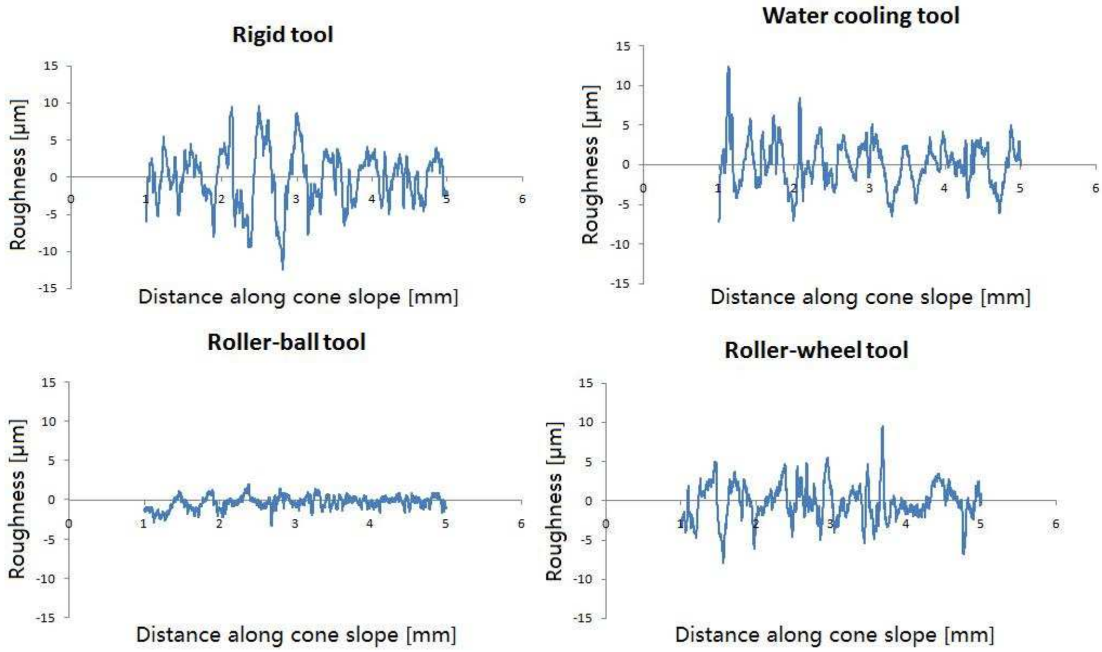


Fig. 13 Surface roughness of truncated cones formed by different tools

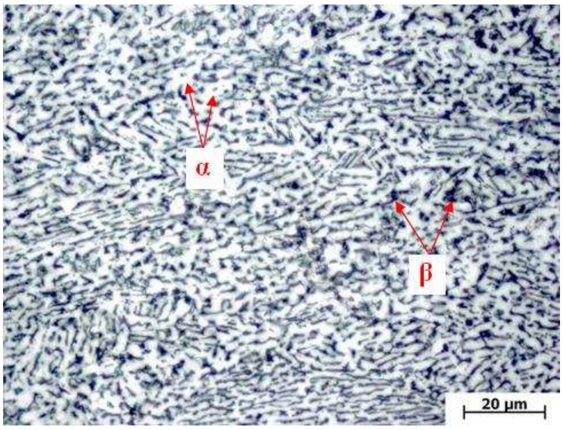
Table 1 Surface roughness of truncated cones formed by different tools (units: μm)

	Rigid tool	Water cooled tool	Roller-ball tool	Roller-wheel tool
Ra	2.939	2.348	0.805	1.731
Rq	3.661	3.029	1.092	2.25
Rz	17.226	15.116	4.64	9.327

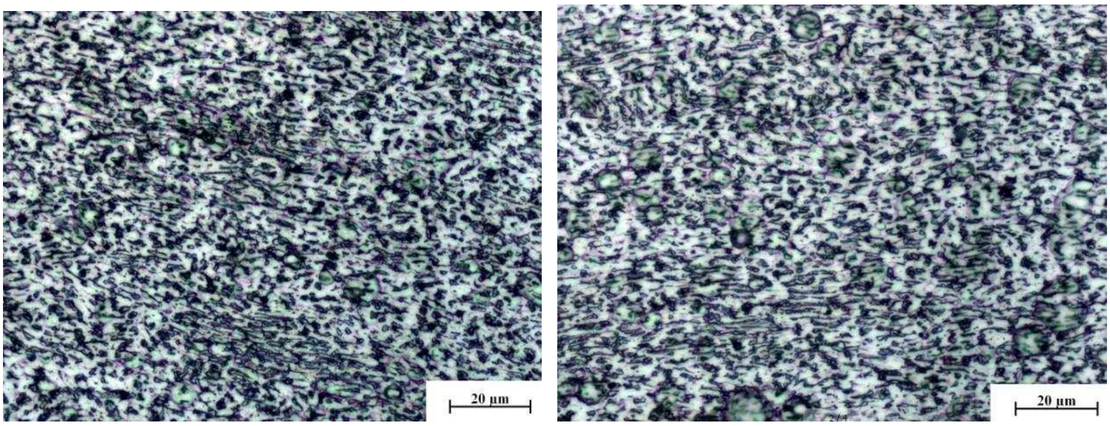
4.4Microstructure

After forming process, optical microstructures of the truncated cones formed by different tools were investigated. As Ti6Al4V is a typical two phase (α+β) alloy, Fig, 14(a) shows the initial microstructure of the sheet. As can be seen from the figure, the base matrix consists of duplex microstructure with primary equiaxed α phase and acicular β phase, which distributes in the interface of zonal α phase. Meanwhile, it indicates that the content of α phase is higher than that of β phase. The optical microstructures of the truncated cones formed by different forming tools are shown in

Fig. 14(b)-(e). There is no obvious distinction among the four metallographs. From the figure, it can be also found that small fraction volume of the matrix (α+β) has been broken after ISF due to the high pressure provided by the forming tools. On the other hand, since the total heating time for each part is only about 10 minutes and the forming temperature of the plate during ISF is about 500°C, it is not high enough to reach the recrystallization temperature (750°C for Ti6Al4V) and the phase transformation temperature (970°C initial for β). These broken grains are not likely to grow and to initiate phase transformation. From what have been discussed above, it can be concluded that the synthetical mechanical properties of the plate after ISF with different forming tools may be improved with the finer grain size, which gives E-ISF another advantage.

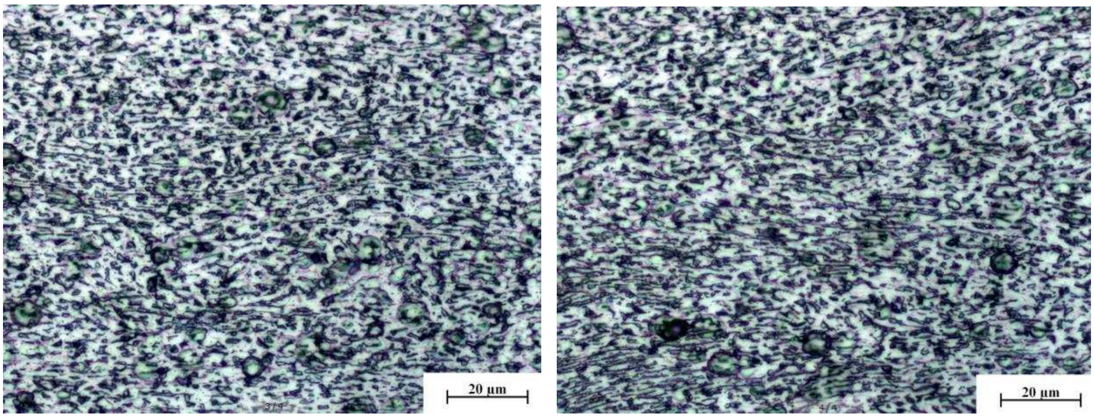


(a) Original sheet



(b)Formed by Rigid tool

(c)Formed by Water cooled tool



(d)Formed by Roller-ball tool (e)Formed by roller-wheel tool

Fig. 14 Microstructure before and after forming

4.6 Discussion

Based on the investigative work as reported from the above, the E-ISF processing of titanium alloy is certainly much more challenging than other types of materials such as magnesium and aluminum alloys. ISF processing at elevated temperature is essential for achieving sufficient formability and this demands an even more stringent requirement for the design and selection of E-ISF tools. However, due to the high resistance of titanium alloy, lower current of 200-300A can be used comparing to magnesium or aluminum alloys. Thus the electric discharge can be minimized under good friction condition.

By evaluating the sheet microstructure, there is no obvious difference for the parts formed by different tools. However, concerning the tool wear and sheet surface quality, it can be found that the roller-ball tool is the best solution for E-ISF processing of titanium alloy Ti6Al4V. Comparing to the rigid type tool, the rolling friction condition employed by the roller-ball tool could avoid severe scratches on the sheet surface and excessive tool wear. Comparing to the rolling-wheel tool, the universal rolling direction of the ball provides extra flexibility. In addition, this roller-ball tool is much easier to manufacture as compared to the roller-wheel tool and even the water cooled tool. The ball at the tool end can be replaced at very low cost whenever necessary. The roller-ball tool shows good potential in the E-ISF application. However, a part with vertical wall angle cannot be directly processed by using the developed roller-ball tool, which is a potential drawback. The design may be further improved by employing the concept of an obsolete roller-ball tool that mentioned in previous work [18].

4 Conclusions

In this paper, novel E-ISF tools were designed and tested for the improvement of surface quality in forming of Ti6Al4V sheet. From the temperature data obtained, it was found that with the water cooling design, the tool temperature can be well controlled to approximately 100ºC as compared to the forming temperature of over 500ºC. By changing friction mode from sliding to rolling friction, both roller-ball tool and roller-wheel tool show a good performance in terms of improvement of surface roughness. The developed tools can be used not only in the E-ISF process, but also other hot ISF processes such as laser assisted ISF.

The conclusions of this work can be summarized as follows:

1) By reducing the tool temperature through the employment of a water cooled system, the tool wear can be reduced and the adhesion of sheet material on the tool tip can be minimized.

2) By employing the roller ball tool, surface scratch and the electric discharge can be avoided with much improved surface finish.

3) The use of the water cooled tool doesn’t have significant impact on the material metallurgical structure.

In this work, the sheet forming temperature was maintained by manual adjustment of current based on temperature observation. In the future work, a more precise control over forming temperature can be developed by using closed loop control system.

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References

1. Ji, Y.H. and J.J. Park, *Formability of magnesium AZ31 sheet in the incremental forming at warm temperature.* Journal of Materials Processing Technology, 2008. **201**(1-3): p. 354-358.
2. Ambrogio, G., L. Filice, and G.L. Manco, *Warm incremental forming of magnesium alloy AZ31.* Cirp Annals-Manufacturing Technology, 2008. **57**(1): p. 257-260.
3. Duflou, J.R., et al., *Laser assisted incremental forming: Formability and accuracy improvement.* CIRP Annals-Manufacturing Technology, 2007. **56**(1): p. 273-276.
4. Duflou, J.R., et al., *Improved SPIF performance through dynamic local heating.* International Journal of Machine Tools & Manufacture, 2008. **48**(5): p. 543-549.
5. Göttmann, A., et al., *Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts.* Production Engineering, 2011. **5**(3): p. 263-271.
6. Gottmann, A., et al., *A novel approach for temperature control in ISF supported by laser and resistance heating.* International Journal of Advanced Manufacturing Technology, 2013. **67**(9-12): p. 2195-2205.
7. Otsu, M., et al., *Friction stir incremental forming of aluminum alloy sheets.* Steel Res Int, 2010. **81**(9): p. 942-945.
8. Buffa, G., D. Campanella, and L. Fratini, *On the improvement of material formability in SPIF operation through tool stirring action.* The International Journal of Advanced Manufacturing Technology, 2012: p. 1-9.
9. Xu, D., et al., *Mechanism investigation for the influence of tool rotation and laser surface texturing (LST) on formability in single point incremental forming.* International Journal of Machine Tools and Manufacture, 2013. **73**(0): p. 37-46.
10. Fan, G.Q., et al., *Electric hot incremental forming: A novel technique.* International Journal of Machine Tools & Manufacture, 2008. **48**(15): p. 1688-1692.
11. Fan, G.Q., et al., *Electric hot incremental forming of Ti-6Al-4V titanium sheet.* International Journal of Advanced Manufacturing Technology, 2010. **49**(9-12): p. 941-947.
12. Fan, G. and L. Gao, *Mechanical property of Ti-6Al-4V sheet in one-sided electric hot incremental forming.* The International Journal of Advanced Manufacturing Technology, 2014: p. 1-6.
13. Ambrogio, G., L. Filice, and F. Gagliardi, *Formability of lightweight alloys by hot incremental sheet forming.* Materials & Design, 2012. **34**: p. 501-508.
14. Nam, N.T., *Hot Incremental Forming Of Magnesium And Aluminum Alloy Sheets By Using Direct Heating System.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2013.
15. Zhang, Q.L., et al., *Warm negative incremental forming of magnesium alloy AZ31 Sheet: New lubricating method.* Journal of Materials Processing Technology, 2010. **210**(2): p. 323-329.
16. Rong Shean Lee and H.C. Lin., *Process design based on the deformation mechanism for the non-isothermal forging of Ti–6Al–4V alloy.* Journal of Materials Processing Technology, 1998. **79**: p. 224-235.
17. Y.H. Kim and J.J. Park., *Effect of process parameters on formability in incremental forming of sheet metal.* Journal of Materials Processing Technology, 2002. **130-131**: p. 42-46.
18. Lu, B., et al., *Mechanism investigation of friction-related effects in single point incremental forming using a developed oblique roller-ball tool.* International Journal of Machine Tools and Manufacture, 2014. **85**: p. 14-29.