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Improvement of the Dimensional Accuracy of a Ti-6Al-4V Ripple Disc During Electric Hot Incremental Sheet Forming

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The edge warpage of a Ti-6Al-4V ripple disc is a major forming defect during electric hot incremental forming, which can lead to a significant dimensional error. In this paper, a novel manufacturing method, namely the combination of electric hot incremental forming and electrically assisted sizing, has been proposed to improve the forming defect. The effect of process parameters on forming fracture was analysed in detail, and then an optimal combination of process parameters was obtained to ensure the successful forming of a Ti-6Al-4V ripple disc. On this basis, a sizing device and a sizing current were separately designed and analysed to eliminate the warpage defect of Ti-6Al-4V ripple discs. According to the experimental result, Ti-6Al-4V ripple discs can be satisfactorily fabricated through the method proposed.

Keywords: incremental sheet forming, electric hot forming, electrically assisted sizing, edge warpage, ripple disc

Highlights
- *A novel forming process that combines electric hot incremental forming and electrically assisted sizing of Ti-6Al-4V ripple discs is proposed to fabricate the part.*
- *The suitable current value is obtained to fabricate Ti-6Al-4V ripple discs in electric hot forming.*
- *The effect of main forming parameters, such as feed rates and step size, on the forming quality of the part is analysed in detail.*
- *A sizing device and a sizing current are separately designed and analysed to improve the forming accuracy of Ti-6Al-4V ripple discs.*

0 INTRODUCTION

The formability of materials is enhanced during incremental sheet forming, and the lower forming accuracy of parts is also obtained due to the local forming characteristics, namely that the forming region between the tool and the sheet has a springback with the removal of the tool; consequently, the application of this technology can be restricted. To solve this problem, various efforts, in Taguchi desirability function analysis [1], process optimization [2], optimal forming strategies [3], grey relation analysis [4], and considering tool deformation [5], are executed to improve the forming accuracy of parts The sum of clamping, non-clamping, and final errors is the manufacturing error of parts in incremental sheet forming and it is often less than or equal to ± 3 mm according to the study of Oleksik et al. [2] Currently, auxiliary support, path compensation, and process optimization are separately adopted to reduce the fabricating error of parts [6] to [9]. Although some assistant forming schemes [10] are proposed to enhance the dimensional accuracy of parts in the forming process, the manufacturing cost is increased due to the fact that the complexity of the whole process can be improved. Therefore, the latter two methods remain major ways of enhancing the forming quality of parts during incremental sheet forming.

The deformation mechanism of materials is more complex in electric hot incremental forming (EHIF), and the effect factors of dimensional accuracy are mainly process parameters, thermal expansion, and residual stress [11]. Saidi et al. adopted the cartridge heater to fabricate the part of titanium alloy Ti-6Al-4V below the recrystallization temperature [12]. Xu et al. adopted the self-lubricating method to improve the surface quality of TA1 sheet [13]. Mohanraj et al. proposed a thermal model to predict the forming region temperature during the electric heating incremental sheet forming [14]. Wu et al. further analysed the characterization of material flow for the hot incremental sheet-forming process of dissimilar sheet metals [15]. Ajay adopted the optimal method of process parameters to improve the forming quality of titanium alloy in incremental sheet forming [16]. Fan et al. [17] employed a composite process, namely reverse drawing and EHIF, to enhance the axial forming accuracy of parts with Ti-6Al-4V. On this basis, Ambrogio et al. [18] further adopted an energy density function to analyse the energy level of

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different alloys, such as AA2024-T3, AZ31B-O, and Ti-6Al-4V alloys, and then the mapping relationship between forming angle and minimum energy level was established. Furthermore, Skjoedt et al. [19] and Shi et al. [20] separately proposed a modified spiral forming path to enhance the manufacturing accuracy of parts.

According to the above studies, some typical parts, such as cone and square cone, are adopted to analyse the optimal method of dimensional accuracy [21] to [23]. However, the heteromorphic part, namely a ripple disc, is still rarely reported in recent studies, and its forming defect, namely that is obtained due to the interaction between residual stress and thermal expansion, is shown in Fig. 1. In this paper, a novel manufacturing method, the combination of EHIF and electrically assisted sizing (EAS), was proposed to improve forming defects of the ripple disc. The effect of process parameters on forming fracture was analysed in detail, and then an optimal combination of process parameters was obtained to ensure the successful forming of Ti-6Al-4V ripple discs. On this basis, a sizing device and a sizing current were separately designed and analysed to eliminate the warpage defect of Ti-6Al-4V ripple discs. The

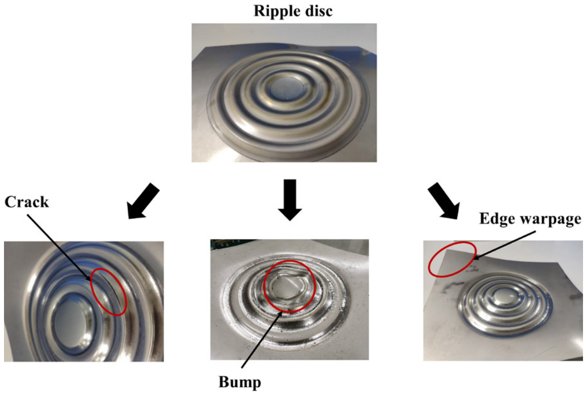

Fig. 1. *Forming defects of a ripple dis*

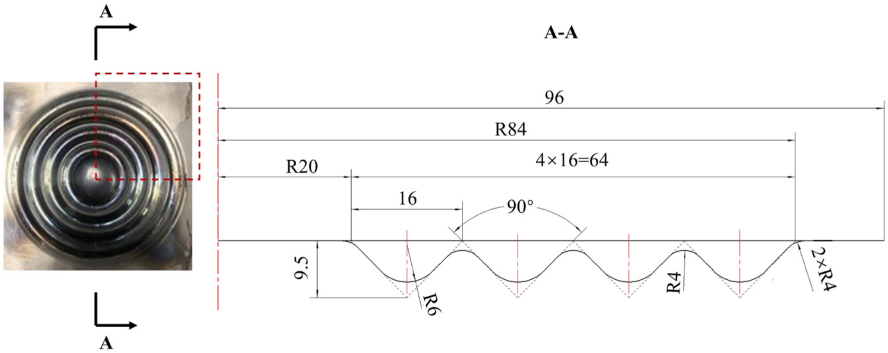

Fig. 2. *Sketch of the forming profile of parts; units in mm*

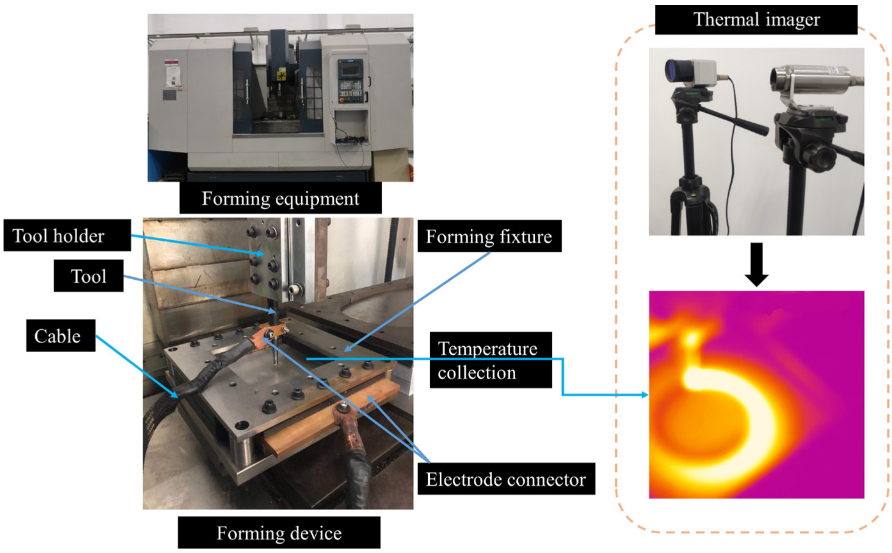

Fig. 3. *The test setup of the ripple disc in EHIF*

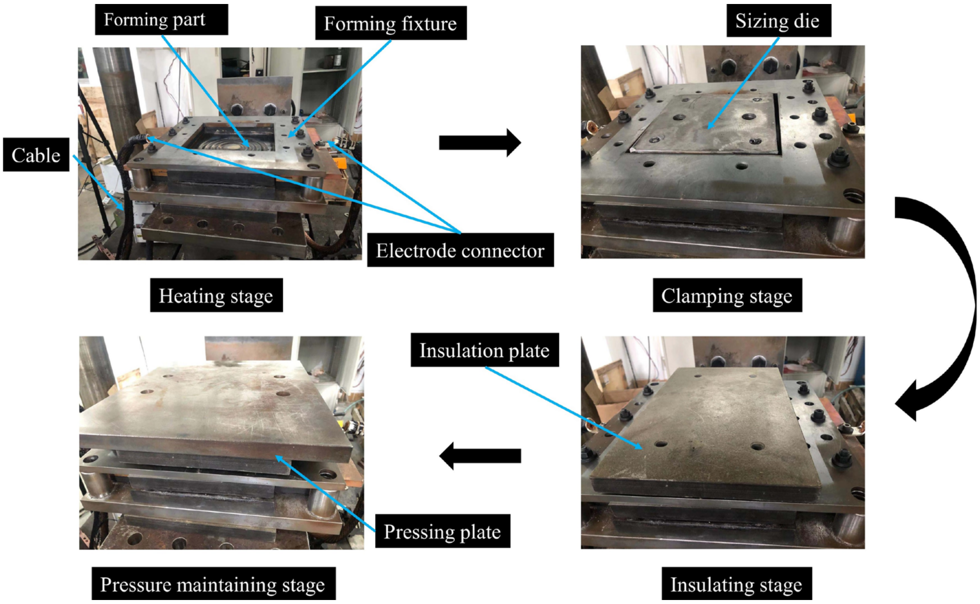

Fig. 4. *The sizing process of the ripple disc*

proposed novel method can be used to rapidly fabricate the ripple disc for the aerospace field and be also further expanded to the forming of other similar parts for other fields, such as the automotive industry, biomedicine, rail transit, and the like.

1 METHODS

A ripple disc with Ti-6Al-4V titanium alloy is fabricated to analyse the effect of forming and sizing process parameters on forming quality, the dimension of which is shown in Fig. 2. The part with 0.8 mm thickness is fabricated in a numerical control machine (Producer: LNC Technology CO., Ltd., Taiwan; Type: LNC-M700; Machine range: 1400 mm for *x*-axis, 700 mm for *y*-axis, and 700 mm for *z*-axis). Meanwhile, a direct-current power (current range of 0 A to 1500 A) and a thermal imager (Producer: Shenzhen Ce-temp Technology Co., Ltd., China; Type: PI1M-PI80x; Range: –20 °C to 1500 °C; Error: ±0.1 °C) are separately adopted to provide the heat and to collect temperature for the forming region, which is shown in Fig. 3.

The warpage defect of parts remain, and then an electrically assisted sizing process, as shown in Fig. 4, is designed to improve the forming defect. The four stages (i.e., heating, clamping, pressure-maintaining, and insulating) are designed in the sizing process, in which the last three stages are used to ensure the sizing force and the sizing time, and the first stage is used to provide a reliable sizing temperature.

2 EXPERIMENTAL

2.1 Electric Hot Incremental Forming Experiments

Fig. 5 shows the forming strategy of ripple disc, and the two stages are adopted to fabricate the part. The first forming path is designed to obtain the lateral wall of ripple disc, and the opposite wall is fabricated according to the second forming path. Meanwhile, some process parameters, such as current, feed rate and step size, are selected to analyse the forming quality of ripple disc, and the corresponding experimental scheme is shown in Table 1. In the sizing stage, the heating method, namely electrically assisted integral heating, is different from the local heating method of forming stage. Therefore, a high-power

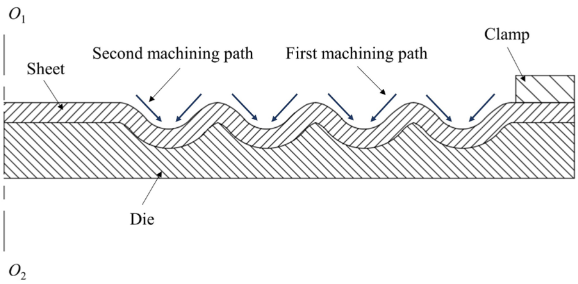

Fig. 5. *The forming strategy of the ripple disc*

pulse power (current range of 0 A to 15000 A) is adopted to realize the integral heating of sheet metal. Current values from 2200 A to 3000 A are separately used to heat the sheet, and the max holding time is 35 min in order to reduce the oxidation phenomenon of Ti-6Al-4V titanium alloy.

Table 1. *The forming experimental scheme of the ripple disc*

No.	Current [A]	Feed rate [mm/min]	Step size [mm]
1	75	900	0.2
2	202	900	0.2
3	220	900	0.2
4	350	900	0.2
5	220	300	0.2
6	220	1500	0.2
7	220	900	0.4
8	220	900	0.6

2.2 Electrically Assisted Sizing Experiments

The reference annealing temperature of Ti-6Al-4V titanium alloy is 600 °C to 650 °C, and the keep-warm time is 60 min to 240 min in the traditional annealing process. In the electrically assisted sizing process, five current values, (2200 A, 2400 A, 2600 A, 2800 A, and 3000 A) are designed according to the traditional annealing process, and the isothermal surface of parts is viewed as a saturated temperature of the annealing process, as shown in Fig. 6. The corresponding saturated temperatures are 563.7 °C, 593.6 °C, 623.5 °C, 652.3 °C, and 684.1 °C, respectively. Meanwhile, the heating time for the electrically assisted sizing process should be less than the keep-warm time of the traditional annealing process due to the high-temperature oxidation defect of Ti-6Al-4V titanium alloy. Therefore, 10 min, 15 min, 20 min, 25 min, 30 min, and 35 min are respectively used to analyse the change of h, in which h is the warpage height of the part edge.

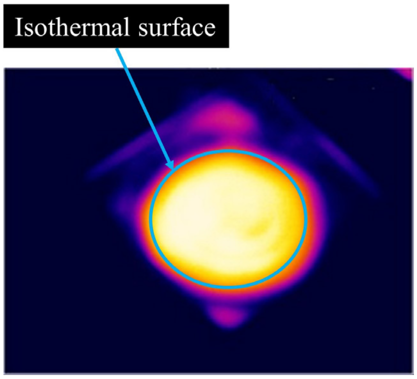

Fig. 6. *The thermal imaging photo of the isothermal surface of parts*

3 RESULTS AND DISCUSSION

3.1 Effect of Current Intensity on Forming Quality

Four experimental groups (no. 1 to no. 4) are adopted to analyse the effect of current intensity on forming quality according to Table 1. The height (h) of the warpage is viewed as a major forming defect, and the crack and the bump are further used to estimate the feasibility of the parameters designed. Fig. 7 shows the effect of current intensities on forming defects, and the value of h increases with the increase of current intensity when the current intensity is less than 200 A. Meanwhile, the value of h is basically unchanged in the range of 202 A to 350 A, the springback is significant under the action of 75 A current, the crack is obtained under the action of 202 A current, and the bump is acquired under the action of 350 A current. According to the above analysis, the springback is a major defect when the current intensity is lower, and the interaction of thermal stress and springback is a major factor when the current value is greater than 200 A, in which the thermal stress is a main inducing factor of forming defects. Therefore, the current of

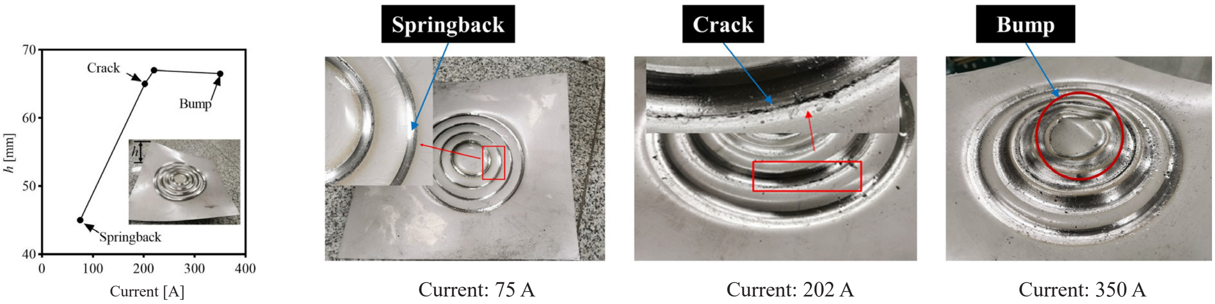

Fig. 7. *The effect of current intensity on forming defects*

220 A is a suitable current parameter in the EHIF of ripple disc.

3.2 Effect of Feed Rates on Forming Quality

Fig. 8 shows the effect of feed rate on forming quality, in which the warpage of parts is both existent under the action of each feed rate. Meanwhile, the bump is obtained at the centre of parts when the feed rate is 300 mm/min, which is caused due to the effect of thermal stress. The springback is significant under the action of 1500 mm/min feed rate because a large deformation resistance is obtained due to the fact that the forming temperature is lower than the other two experiments. Therefore, a feed rate of 900 mm/min is selected to fabricate the part according to the above analysis.

3.3 Effect of Step Size on Forming Quality

Based on the current of 220 A and the feed rate of 900 mm/min, three step sizes (0.2 mm, 0.4 mm, and 0.6 mm) are separately used to analyse the forming quality of parts. Fig. 9 shows the effect of step size on forming quality, and the warpage of parts is still obtained in the three experiments. Meanwhile, the forming part would produce a crack under the action of 0.4 mm and 0.6 mm, and the crack increases with the increase of step size. The contact area between tools and sheets increases with the increase of step size, which leads to the actual forming temperature being less than the temperature planned. Therefore, the plasticity of materials is reducing with the increase of step size, and then the crack defect is easily obtained when the step size is large.

3.4 Improvement on Warpage Defect

According to the aforementioned analysis, the combination of process parameters (220 A, 900 mm/min, and 0.2 mm) is adopted to obtain a ripple disc without crack- and bump-defect. However, the warpage defect of the parts remains, and then an electrically assisted sizing process is adopted to eliminate the defect.

Fig. 10 shows the effect of sizing current and time on *h*, in which the value of *h* is negatively correlated with time and current. The effect of sizing time on h is less than that of the sizing current. *h* is 30.6 mm under the interaction of 2200 A and 10 min to 15 min, and it is a maximum in sizing experiments. In each current, the value of h from 20 min to 25 min is both

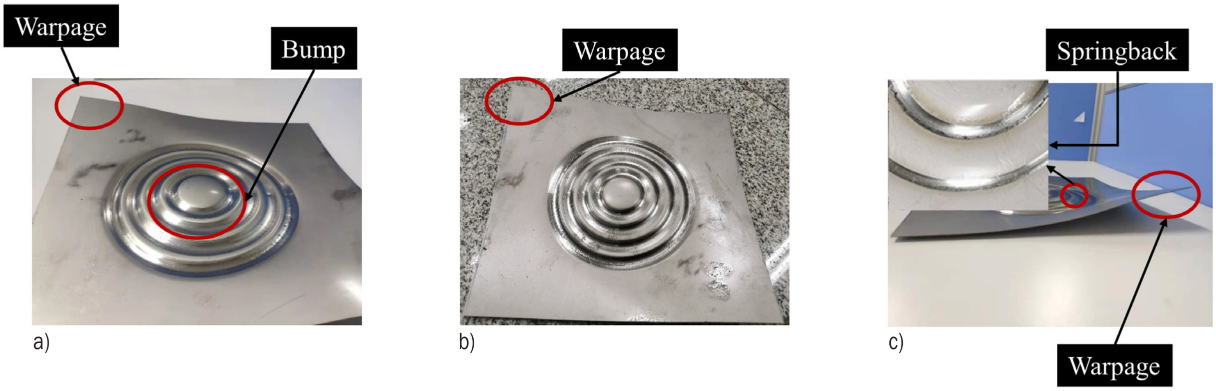

Fig. 8. *The effect of feed rates on forming defects; a) 300 mm/min, b) 900 mm/min, c) 1500 mm/min*

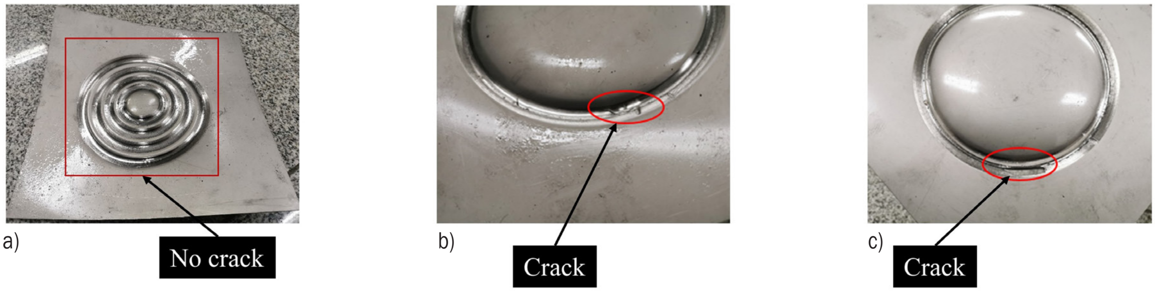

Fig. 9. *The effect of step sizes on forming defects; a) 0.2 mm, b) 0.4 mm, c) 0.6 mm*

between 15 min and 30 min. Meanwhile, *h* of 2.1 mm is obtained under the interaction of 3000 A and 30 min to 35 min, and the value of *h* is far less than the blank holder distance (53.5 mm). According to Saint Venant's principle, the distribution of stresses or displacements in a structure remains nearly unchanged at a sufficiently distant point from the region of interest, as long as the external loads or boundary conditions remain the same. Therefore, an *h* of 2.1 mm has no influence on the dimensional accuracy of ripple disc according to the above principle. In addition to this, a long heating time can easily lead to the oxidation defect of Ti-6Al-4V titanium alloy. Consequently, the setup of 3000 A and 30 min is an optimal combination of sizing parameters, which can significantly eliminate the warpage defect caused by the forming stage.

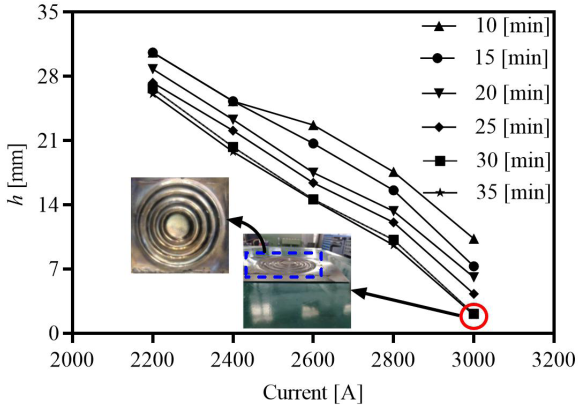

Fig. 10. *Difference between different sizing parameters*

4 CONCLUSIONS

Aiming to eliminate the forming defect of ripple disc, a novel manufacturing scheme, namely the combination of EHIF and electrically assisted sizing, is proposed to improve fabricating defects, such as crack, bump, and warpage. The crack and the bump are improved through optimizing process parameters in the forming stage, the warpage is an inherent forming defect of Ti-6Al-4V ripple disc, and it is not eliminated through adjusting process parameters. Therefore, an optimal combination of forming process parameters, namely 220 A, 900 mm/min, and 0.2 mm, is selected to fabricate the part according to experimental analysis results. On this basis, the effect of sizing current and time on *h* is further analysed in detail, and h is negatively correlated with time and current, and the effect of sizing time on *h* is less than that of the sizing current. Finally, the combination of sizing parameters, containing 3000 A and 30 min, is set to eliminate the warpage defect of ripple disc in the sizing stage.

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8 REFERENCES

[1] Bishnoi, P., Chandna, P. (2023). Improved geometric accuracy in single-point incremental forming of aerospace superalloy 625 using Taguchi desirability function analysis. *Aircraft Engineering and Aerospace Technology*, vol. 95, no. 7, p. 0339, **DOI:10.1108/AEAT-12-2022-0339**.

[2] Oleksik, V., Trzepiecinski, T., Szpunar, M., Chodola, L., Ficek, D., Szczesny, I. (2021). Single-point incremental forming of titanium and titanium alloy sheets. *Materials*, vol. 14, no. 21, p. 6372, **DOI:10.3390/ma14216372**.

[3] Sbayti, M., Ghiotti, A., Bahloul, R., BelhadjSalah, H., Bruschi, S. (2022). Effective strategies of metamodeling and optimization of hot incremental sheet forming process of Ti6Al4Vartificial hip joint component. *Journal of Computational Science*, vol. 60, p. 101595, **DOI:10.1016/j.jocs.2022. 101595**.

[4] Jagtap, R., Kakandikar, G., Dhanawade, A., More, S. (2021). Optimization of wall thickness and geometric accuracy in stretch forming combined with incremental sheet forming using grey relational analysis (GRA). *Materials Today: Proceedings*, vol. 44, p. 4393-4398, **DOI:10.1016/j. matpr.2020.10.574**.

[5] Zhu, H., Han, F.C., Liu, Y.B. (2018). The effect of the extrusion direction on the incremental forming quality considering tool deformation. *The International Journal of Advanced Manufacturing Technology*, vol. 97, p. 1835-1846, **DOI:10.1007/s00170-018-2069-8**.

[6] Milutinovic, M., Lendjel, R., Balos, S., Zlatanovic, D.L., Sevsek, L., Pepelnjak, T. (2021). Characterisation of geometrical and physical properties of a stainless steel denture framework manufactured by single-point incremental forming. *Journal of Materials Research and Technology*, vol. 10, p. 605-623, **DOI:10.1016/j.jmrt.2020.12.014**.

[7] Lu, H.B., Kearney, M., Liu, S., Daniel, W.J.T., Meehan, P.A. (2016). Two directional toolpath correction in single-point incremental forming using model predictive control. *The International Journal of Advanced Manufacturing Technology*, vol. 91, p. 91-106, **DOI:10.1007/s00170-016-9672-3**.

[8] Schreiber, R.G., Schaefferb, L. (2019). Manufacture of absorber fins for solar collector using incremental sheet forming. *Journal of Materials Research and Technology*, vol. 8, no. 1, p. 1132-1140, **DOI:10.1016/j.jmrt.2018.07.018**.

[9] Li, Z., He, S., An, Z., Gao, Z., Lu, S. (2023). Multi-objective optimization of dimensional accuracy in electric hot incremental sheet forming. *Coatings*, vol. 13, no. 5, p. 923, **DOI:10.3390/coatings13050923**.

[10] Ambrogio, G., Palumbo, G., Sgambitterra, E., Guglielmi, P., Piccininni, A., De Napoli, L., Villa, T., Fragomeni, G. (2018). Experimental investigation of the mechanical performances of titanium cranial prostheses manufactured by super plastic forming and single-point incremental forming. *The International Journal of Advanced Manufacturing Technology*, vol. 98, p. 1489-1503, **DOI:10.1007/s00170-018-2338-6**.

[11] Ao, D.W., Gao, J., Chu, X.R., Lin, S.X., Lin, J. (2020). Formability and deformation mechanism of Ti-6Al-4V sheet under electropulsing assisted incremental forming. *International Journal of Solids and Structures*, vol. 202, p. 357-367, **DOI:10.1016/j.ijsolstr.2020.06.028**.

[12] Saidi, B., Moreau, L.G., Cherouat, A., Nasri, R. (2020). Experimental and numerical study on warm single-point incremental sheet forming (WSPIF) of titanium alloy Ti-6Al-4V, using cartridge heaters. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 43, p. 1-15, **DOI:10.1007/s40430-020-02632-8**.

[13] Xu, C.X., Li, Y.L., Wang, Z.J., Cheng, Z.N. Liu, F.Y. (2020). The influence of self-lubricating coating during incremental sheet forming of TA1 sheet. *The International Journal of Advanced Manufacturing Technology*, vol. 110, p. 2465-2477, **DOI:10.1007/s00170-020-06013-2**.

[14] Mohanraj, R., Elangovan, S. (2020). Thermal modeling and experimental investigation on the influences of the process parameters on warm incremental sheet metal forming of titanium grade 2 using electric heating technique. *The International Journal of Advanced Manufacturing Technology*, vol. 110, p. 255-274, **DOI:10.1007/s00170-020-05851-4**.

[15] Wu, R.H., Li, M., Liu, X.M., Cai, S., Chen, J. (2020). Characterization of material flow in friction stir-assisted incremental forming with synchronous bonding of dissimilar sheet metals. *The International Journal of Advanced Manufacturing Technology*, vol. 109, p. 2523-2534, **DOI:10.1007/s00170-020-05782-0**.

[16] Ajay, C.V. (2020). Parameter optimization in incremental forming of titanium alloy material. *Transactions of the Indian Institute of Metals*, vol. 73, p. 2403-2413, **DOI:10.1007/s12666-020-02044-1**.

[17] Fan, G.P., Gao, L. (2014). Mechanical property of Ti-6Al-4V sheet in one-sided electric hot incremental forming. *The International Journal of Advanced Manufacturing Technology*, vol. 72, p. 989-994, **DOI:10.1007/s00170-014-5733-7**.

[18] Ambrogio, G., Filice, L., Gagliardi, F. (2012). Formability of lightweight alloys by hot incremental sheet forming. *Materials & Design*, vol. 34, p. 501-508, **DOI:10.1016/j.matdes.2011.08.024**.

[19] Skjoedt, M., Hancock, M.H., Bay, N. (2007). Creating helical tool paths for single point incremental forming. *Key Engineering Materials*, vol. 344, p. 583-590, **DOI:10.4028/www.scientific.net/KEM.344.583**.

[20] Shi, X.F., Gao, L., Khalatbari, H., Xu, Y., Wang, H., Jin, L.L. (2013). Electric hot incremental forming of low carbon steel sheet: accuracy improvement. *The International Journal of Advanced Manufacturing Technology*, vol. 68, no. 1, p. 241-247, **DOI:10.1007/s00170-013-4724-4**.

[21] Maass F., Hahn M., Tekkaya A.E. (2020). Interaction of Process Parameters, Forming Mechanisms, and Residual Stresses in Single Point Incremental Forming. *Metals*, vol. 10, no. 5, p. 665, **DOI:10.3390/met10050656**.

[22] Sevšek, L., Šegota, S.B., Car, Z., Pepelnjak, T. (2023). Determining the influence and correlation for parameters of flexible forming using the random forest method. *Applied Soft Computing*, vol. 144, art. ID 110497, **DOI:10.1016/j.asoc.2023.110497**.

[23] Trzepiecinski, T., Szpunar, M., Dzierwa, A., Zaba, K. (2022). Investigation of surface roughness in incremental sheet forming of conical drawpieces from pure titanium sheets. *Materials*, vol. 15, p. 4278, **DOI:10.3390/ma15124278**.