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A CRITICAL REVIEW AND INSIGHTS INTO INCREMENTAL SHEET FORMING PROCESS, PARAMETERS, AND APPLICATIONS

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Abstract

There is a growing need and keen interest among the scientific and industrial communities across the globe to thrive for improve manufacturing technologies as well as production processes with a clear objective to have more flexible, economical, time saving as well as minimal material wastage processes. In current scenario, the driving force for the manufacturers is to solve the challenges pertinent to geometrical conformity, quality of manufactured parts and productivity by innovating and evolving the current set of manufacturing methods. In recent past There is a significant and rapid technological advancement in the sheet metal forming processing of metals and alloys especially in automotive, aerospace, defence, marine sectors. Incremental sheet metal forming or dieless forming process is one of the unique methods which has gained widespread attention in lass few decades. This paper provides insights and critical review on the incremental sheet forming in terms of formability and forming limit, deformation and failure Mechanics, forming methods, materials, tools, surface quality, springback, process accuracy, toolpath strategies, numerical approaches and simulation. Sheet metal forming belongs to that category of metal forming operations wherein flat metal sheets are plastically deformed to achieve the necessary product. Forming can be performed under compressive, tensile, bending and shearing conditions. There exists a wide array of forming operations utilizing different techniques, but with introduction of computers there has been a surge in the flexibility of manufacturing processes. With a growing need of complex designs in industry at low cost, the spotlight is now on incremental sheet forming (ISF). The ability to form non-symmetrical parts without the requirement of costly dies gives ISF an edge over other sheet forming processes. Process flexibility and higher formability are other aspects which makes ISF an attractive venture for manufacturing. In the last decades, sizeable amount of work has been done in this field to make it commercially viable; especially in automobile, aerospace and defence sectors. The present paper recapitulates the variety of research carried out in the concerned area in chronological fashion and discusses the areas where more attention is required.

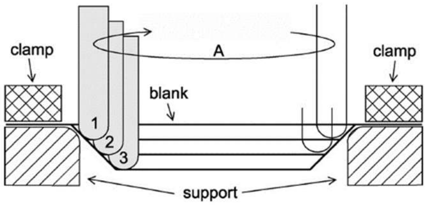
Keywords: Incremental forming, Formability, Localised Deformation, spring back, tool path strategy

1. Introduction

Sheet metal forming belongs to that category of metal forming operations wherein flat metal sheets are plastically deformed to achieve the necessary product. Forming can be performed under compressive, tensile, bending and shearing conditions. There exists a wide array of forming operations utilizing different techniques, but with introduction of computers there has been a surge in the flexibility of manufacturing processes. With a growing need of complex designs in industry at low cost, the spotlight is now on incremental sheet forming (ISF). The ability to form non-symmetrical parts without the requirement of costly dies gives ISF an edge over other sheet forming processes. Process flexibility and higher formability are other aspects which makes ISF an attractive venture for manufacturing. In the last decades, sizeable amount of work has been done in this field to make it commercially viable; especially in automobile, aerospace and defence sectors. The present paper recapitulates the variety of research carried out in the concerned area in chronological fashion and discusses the areas where more attention is required.

Keywords: Incremental forming, Formability, Localised Deformation, SPIF, TPIF, AISF

Incremental sheet forming owes its origin to conventional spinning, shear forming and flow forming processes. These processes are analogous to ISF as they can produce axisymmetric shapes without using expensive dies. Automation has been achieved in these above processes using computer numerical control (CNC), numerical control (NC) and programmable numerical control (PNC) systems, which have provided fast production with the necessity of skilled manpower. However, incremental forming methods have delivered the ease of producing non-symmetrical parts at low cost. Leszak [1] bears the credit for developing the idea of incremental forming, but it lacked technical feasibility during that time. Berghahn [2] from General Electric company also proposed another form of dieless forming, where the blank is rotated with respect to a numerically programmed roller following a spiral path towards the center. Mason's work is believed to be the origin of modern ISF, where he speaks of progressive development of a shape through a spherical roller with the essentiality of a backing material [3]. Iseki and his fellow workers did substantial amount of work, starting from simple setups to CNC machines. They worked on variety of shapes, different materials and manufactured non-symmetrical parts [4–6]. They also used water jet technology as a means to achieve forming [7]. Figure 1 describes Iseki's concept of incremental sheet forming.



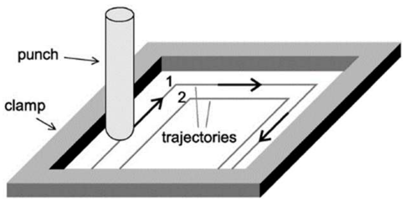


Fig. 1 ISF principle as given by Iseki [4–6].

Kitazawa put forward the concept of incremental stretch expanding by means of multiple passes [8] and two- path stretch expanding of hemispherical [9] and hemi-ellipsoidal shells [10]. Figure 2 depicts the theory of stretch expanding and the mechanism involved. The blank is rotated relative to the tool as in the case of spinning and it is limited to the forming of symmetrical shapes.

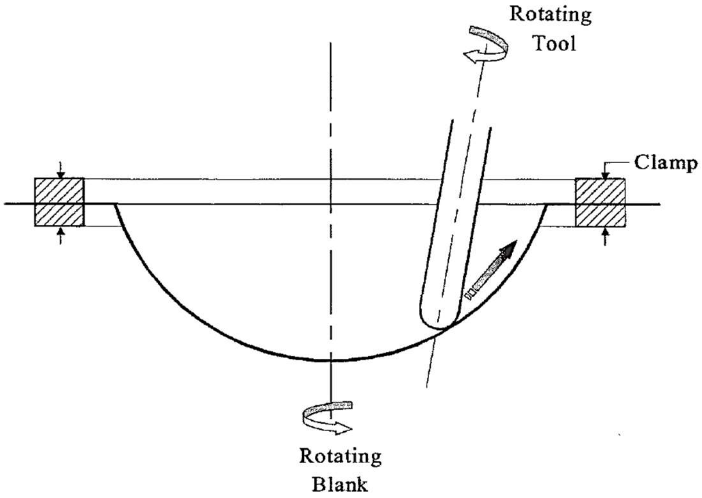


Fig. 2 Incremental stretch expanding apparatus [8]

Figure 3 illustrates the two forming stages involved in expanding of a hemisphere.

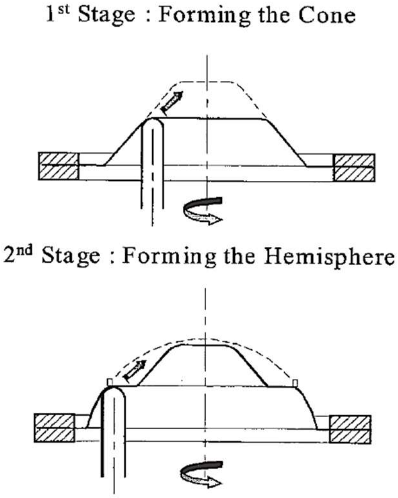


Fig. 3 Multi step formation of a hemisphere [9]

Powell and Andrew [11] gave the initial concept of incremental backward bulge forming which Matsubara [12] utilised for producing low-volume non-symmetrical parts. Contrary to the earlier process, the blank remains stationary with a supporting center and forming occurs only due to tool motion as presented in Figure 4. This variant of incremental forming was later on termed as Two-Point Incremental Forming. Leach et al. [13] have presented backward bulge forming using a standard three-axis CNC milling machine. Jeswiet and Hagan [14] worked on forming concave shapes like automotive light reflector using CNC forming tool which was made to follow a contoured path with depth increments. It is well acknowledged that use of CAD/CAM made modifications of complex components easier.

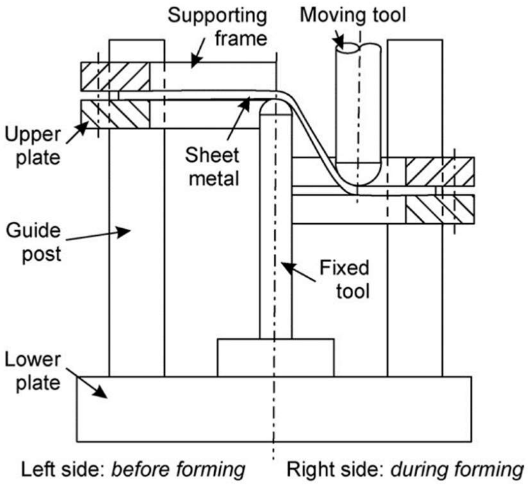


Fig. 4 Backward bulge forming apparatus as proposed by Matsubara [12]

The beginning of 21st century saw tremendous progress in the field of incremental sheet forming. Presently, asymmetric sheet metal incremental forming (AISF) bears the following classifications, which is also shown in Figure 5.

- Single Point Incremental Forming (SPIF), which is defined by a single tool movement over the blank surface.
- Two-Point Incremental Forming (TPIF), where two tools (master and slave tool) are used.
- Two-Point Incremental Forming (TPIF) with Partial Die, where the secondary tool is replaced with a partial die to get the desired shape.
- Two-Point Incremental Forming (TPIF) with Full Die, which involves the movement of the tool over a full die to obtain the required design.

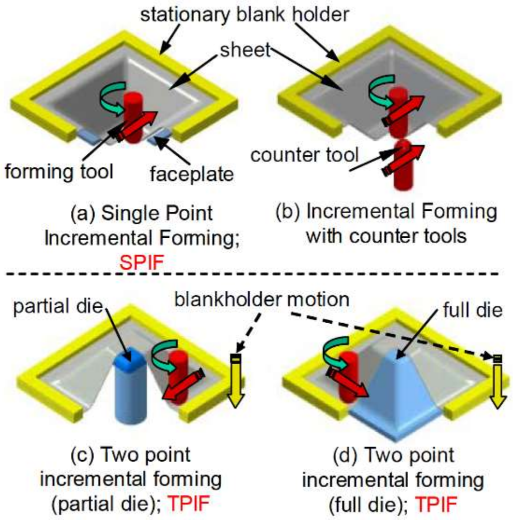


Fig. 5 Variants of asymmetric sheet metal incremental forming [15]

It is very essential to bifurcate the research work into different categories in order to make the discussion easier, as mentioned below:

- Formability and Forming Limits
- Deformation and Failure Mechanics
- Forming Methods
- Forming Materials and Tools
- Forming Forces
- Surface Quality
- Springback
- Process Accuracy
- Toolpath strategies
- Numerical approaches and Simulation

2. Detailed review on different aspects of incremental sheet forming

2.1 Formability and Forming Limits

Formability serves as an important indicator in determining the ease of a sheet metal to attain a desired shape before the occurrence of necking or fracture. Maximum draw angle (φ_{max}) can be defined as the largest angle upto which a sheet can deformed till it fractures. It is considered to be an important parameter in the assessment of formability [16–18]. In relation to the Sine law by Kobayashi [19], it is observed that as the draw angle increases material thickness reduces eventually leading to failure. Micari and Ambrogio suggested to use truncated cone as a benchmark specimen to yield formability results. Limit wall angle (φ_{max}) is derived when fracture occurs for a particular cone angle [20]. Limit wall angle is a crucial factor but it lacks clarity on complex strain state and formability behaviour. Hence, forming limit diagrams (FLD's) which are an effective way of representing the strains developed during the deformation process, are more suitable. Presently, forming limit diagrams are developed as per the methods prescribed by Nakajima [21] and Marciniak [22]. Forming limits are a characteristic of every material and their knowledge leads to optimization of the forming process. Figure 6 shows a characteristic forming limit diagram.

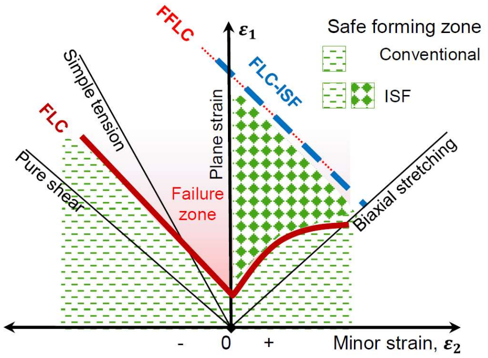


Fig. 6 Depiction of a forming limit diagram (FLD)

Iseki and Kumon [23] carried out initial research on forming limits and stated that incremental sheet forming has higher formability as compared to conventional forming operations. Kim and Yang [24] assumed that shear deformation is instrumental in improving formability and proposed double-pass forming method to achieve the same. They also remarked that ISF needs a new FLD, owing to the difference in its process mechanics from the traditional sheet forming processes. Shim and Park performed dome stretching and ball stretching tests in order to evaluate the formability of an aluminium sheet. The ball tests showed higher forming limits than the dome tests, which resulted in a negative sloped straight line. They stated that ISF is governed by localised deformation, with corners deforming more than the sides. Equi-biaxial stretching takes place at corners whereas plane strain stretching occurs at sides [25]. Figure 7 shows the forming limit diagram for various shapes.

Filice et al. stated that higher strains can be achieved with the process due to localised plastic deformation which is limited to the contact area. They reiterated that the forming limit curve carries the form of a negative sloped straight line located in the positive side of both the axes. With reference to the straining conditions, it was seen that biaxial stretching happens at corners and plane strain stretching between them. In a spiral toolpath, plane strain stretching changes to biaxial with decrease in diameter of the loop [16]. Kim and Park carried out straight groove tests and found out that the ball tool gives higher formability in comparison to the hemispherical head tool. Low feed rate and little friction are effective in refining formability. Planar anisotropic factors cause formability to vary with tool movement variations [26].

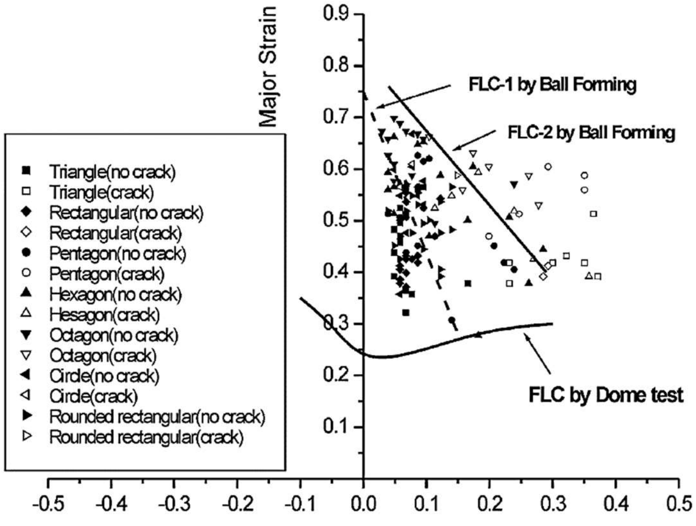


Fig. 7 FLD from various shapes [25]

Park and Kim mentioned that enhanced formability is obtained in case of plane strain stretching and the value of $\varepsilon_{max} + \varepsilon_{min}$ can be considered as a measure of formability. Positive forming method was adjudged to better than negative forming, as the introduction of plane strain stretching increases the forming capability and makes it possible to achieve complex shapes [27]. Visioplastic evaluation and optical deformation measurements indicate that flat surfaces deform by plane strain mode [17]. Hirt et al. [28] specified that elastic deformation of the area around plastic deformation gives rise to hydrostatic pressure, which is the cause of higher strains in ISF. Fratini et al. assessed the correlation between formability and material properties by investigating on many materials. They used statistical analysis to conclude that material formability significantly depends on strain hardening and percentage elongation [29]. Jeswiet and Young found out maximum draw angles for different materials and determined forming limit diagram for a group of different shapes, as shown in Figure 8. They observed that high strains can be achieved by SPIF process [18].

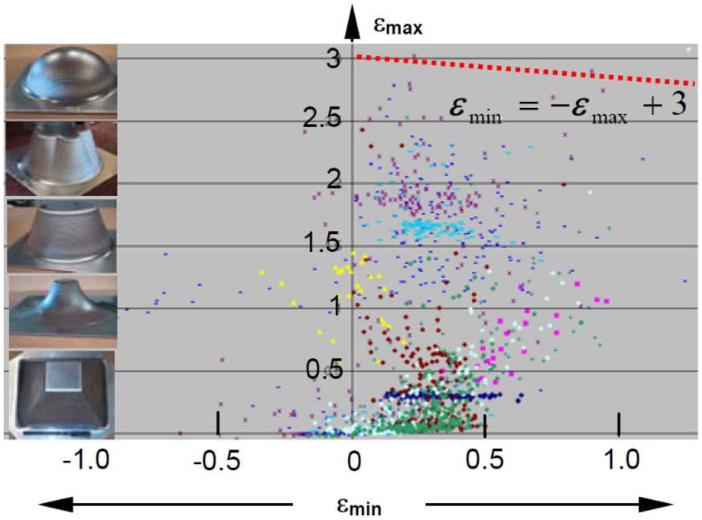


Fig. 8 Combined FLD of different shapes formed from 1.21mm thick 3003-0 aluminium [18]

Formability is affected by factors like material thickness, tool diameter, step size, feed rate, spindle speed, tool rotation direction, forming temperature and forming angle. A summarized view is presented.

Majority of researchers have found that formability increases with material thickness [18,30–38]. In accordance with the sine law, it is considered that as more volume of material interacts with tool, it results in larger forming forces which explains for higher formability. It is worth noting that materials like aluminium, steel and polymer display similar trends. However, few authors have observed deviations from sine law and have considered optimisation in order to gain more formability. Optimisation involved modifying the interaction of material thickness with another parameter (e.g. tool radius) [39–41]. It can be pointed out that thicker sheets are more close to produce strong parts with desired final thickness, hence choosing a thicker sheet is more reliable.

It is of general view that small diameter tools maximise formability, as the deformation zone becomes highly concentrated causing high strain [31,32,35,36,39,42–46]. Also, some papers indicate that other parameters should be considered while assessing increased formability. It means tool diameter should be studied in combination with other parameters [26,41,47–50]. Large diameter tools have a bigger contact zone which is believed to increase forming forces and provide a better support of sheet metal. This has led to the conclusion of some authors that formability can be increased with large diameter tools [34,37,38,51–54]. Figure 9 shows the variation of strains with tool diameter for DC04.

Smaller step size leads to better formability because of progressive deformation. The tool-sheet interface remains localised and there is minimal friction which leads to heavier deformations. Also, there is a decrease in the negative stress distribution at tool-sheet contact area and tensile stresses at the walls [26,31,36,37,39,42–44,46,51,52,55,56]. But, very small step sizes may result in tool wear, increase forming time and repeated application of stresses may lead to early material failure [47,55]. Therefore, it is essential to select proper forming speed and formability values.

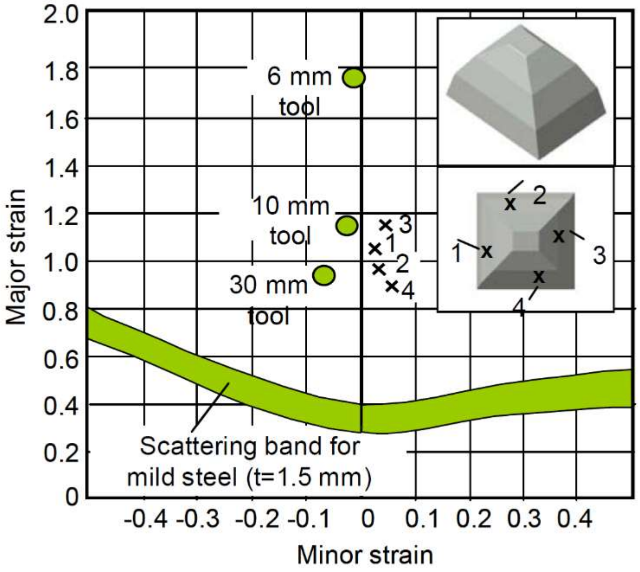


Fig. 9 Tool diameter effects on formability [17]

Feed rate affects formability to a very less extent, still research tells that formability is high at low feed rates. Localised heating or work hardening effect are believed to be the reasons [31,42,49,52]. Optimum feed rates are better at maximising formability and reducing process time [56].

Higher spindle speeds result in heating of tool-sheet contact area due to friction, which in turn causes microstructural changes and formability is seen to increase [31,38,52,57,58]. However, too high speeds can create high friction leading to surface damage. Few authors have found that optimum speeds can give better formability with decent surface finish [55,59].

Obikawa et al. [55] and Durante et al. [44] performed experiments by rotating the tool in different directions and concluded that tool rotation direction does not affect formability.

Maximum forming angle is a significant parameter in the assessment of formability limits of a material. This angle is determined by forming constant wall angle parts each with a steeper wall angle until material failure [25].

Conclusion

The major conclusions drawn from the critical review of incremtenal sheet metal processing of various types of materials, varying process parameters, and processing routes are as follows:

Incremental sheet forming holds the key to rapid manufacturing of complex design at less costs. Extensive work has been witnessed till date, however the process still poses some issues. Time factor is the major lag, with accuracy and quality sharing equal points. An attempt has been made to provide a detailed overview of the forming process.

Formability is an influential aspect in ISF. Improvisation has been carried with the inclusion of multistep strategy, heat supported techniques and effective control of process parameters. Accurate failure prediction is essential along with development of hybrid processes. Optimised toolpaths have resulted in reduction of forces. Still, better algorithms are requisite for quick analysis of forces. Multiple toolpath strategies have been developed for carrying efficient forming. Some have been modulated to counter springback effect. From accuracy point of view, it would be productive to be develop models that deal with real time data so that immediate rectification can happen. Accuracy and precision are core necessities in a quality product. Work on accuracy has seen feature based compensation, regression tools, matrix based predictions in use. Process limits can be enhanced by involving stiffness elements in calculations in addition to error correcting functions. Simulation tools have not gained substantial prediction abilities. Simple shapes are easy to predict and complex shapes take longer durations. Formability and wall angle is dependent on a number of factors; focus should be on devising a proper relationship between these parameters.

References

[1] E. Leszak, Apparatus and process for incremental dieless forming, 1967. Http://www.google.com/patents/US3549577.

[2] Walter G. Berghahn, Lee, J. George F. Murray, Method of dielessly forming surface of revolution, 1967.

[3] B. Mason, Sheet metal forming for small batches, University of Nottingham, 1978.

[4] H. ISEKI, K. KATO, S. Sakamoto, Flexible and incremental sheet metal forming using a spherical roller, in: 40th JJCTP, 1989: p. 44.

[5] H. Iseki, K. Kato, H. Kumon, K. Ozaki, Flexible and Inclemental Sheet Metal Bulging Using a Few Spherical Rollers., Transactions of the Japan Society of Mechanical Engineers Series C. 59 (1993) 2849–2854. Doi:10.1299/kikaic.59.2849.

[6] H. ISEKI, T. NAGANAWA, K. KATO, Flexible and Incremental Sheet Metal Bulging using a Path-Controlled Spherical Roller, Transactions of the Japan Society of Mechanical Engineers Series C. 62 (1996) 1600–1605. Doi:10.1299/kikaic.62.1600.

[7] H. ISEKI, Flexible and Incremental Bulging of Sheet Metal Using High-Speed Water Jet., JSME International Journal Series C. 44 (2001) 486–493. Doi:10.1299/jsmec.44.486.

[8] K. KITAZAWA, A. WAKABAYASHI, K. MURATA, K. YAEJIMA, Metal-flow phenomena in computerized numerically controlled incremental stretch-expanding of

aluminum sheets., Journal of Japan Institute of Light Metals. 46 (1996) 65–70. Doi:10.2464/jilm.46.65.

[9] K. KITAZAWA, S. HAYASHI, S. YAMAZAKI, Hemispherical stretch-expanding of aluminum sheet by computerized numerically controlled incremental forming process with two path method., Journal of Japan Institute of Light Metals. 46 (1996) 219–224. Doi:10.2464/jilm.46.219.

[10] K. KITAZAWA, M. NAKANE, Hemi-ellipsoidal stretch-expanding of aluminum sheet by CNC incremental forming process with two path method., Journal of Japan Institute of Light Metals. 47 (1997) 440–445. Doi:10.2464/jilm.47.440.

[11] N.N. Powell, C. Andrew, Incremental forming of flanged sheet metal components without dedicated dies, ARCHIVE: Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 1989-1996 (Vols 203-210). 206 (1992) 41–47. Doi:10.1243/PIME_PROC_1992_206_054_02.

[12] S. Matsubara, Incremental backward bulge forming of a sheet metal with a hemispherical tool, Japan Society for Technology of Plasticity. 35 (1994) 1311–1316.

[13] A.N. Leach, D., Green, A.J. and Bramley, A new incremental sheet forming process for small batch and prototype parts, in: 9th International Conference on Sheet Metal, 2001: pp. 211–218.

[14] J. Jeswiet, E. Hagan, Rapid prototyping of a headlight with sheet metal, in: Canadian Institute of Mining, Metallurgy and Petroleum, 2001: pp. 109–114.

[15] S. Bambach, M., Hirt, G. And Junk, Modelling and experimental evaluation of the incremental CNC sheet metal forming process, in: Proceedings of the VII-Th International Conference on Computational Plasticity, 2003: pp. 1–15.

[16] L. Filice, L. Fratini, F. Micari, Analysis of Material Formability in Incremental Forming, CIRP Annals - Manufacturing Technology. 51 (2002) 199–202. Doi:10.1016/S0007-8506(07)61499-1.

[17] G. Hirt, S. Junk, N. Witulski, Incremental sheet forming: quality evaluation and process simulation, in: Proceeding of the 7th ICTP Conference, 2002: pp. 925–930.

[18] J. Jeswiet, D. Young, Forming limit diagrams for single-point incremental forming of aluminium sheet, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 219 (2005) 359–364. Doi:10.1243/095440505X32210.

[19] S. Kobayashi, I.K. Hall, E.G. Thomsen, A Theory of Shear Spinning of Cones, Journal of Engineering for Industry. 83 (1961) 485. Doi:10.1115/1.3664573.

[20] F. Micari, G. Ambrogio, A common shape for conducting incremental forming tests, in: Proc of the First Incremental Forming Workshop, University of Saarbrucken, Germany, 2004.

[21] K. Nakazima, T. Kikuma, Forming limits under biaxial stretching of sheet metals, Testu-to Hagane. 53 (1967) 455–458.

[22] Z. Marciniak, Stability of plastic shells under tension with kinematic boundary conditions, Archiwum Mechaniki Stosowanej. 17 (1965) 577–592.

[23] H. Iseki, H. Kumon, Forming limit of incremental sheet metal stretch forming using spherical rollers, Journal of the Japan Society for Technology of Plasticity. 35 (1994) 1337–1342.

[24] T.J. Kim, D.Y. Yang, Improvement of formability for the incremental sheet metal forming process, International Journal of Mechanical Sciences. 42 (2000) 1271–1286. Doi:10.1016/S0020-7403(99)00047-8.

[25] M.-S. Shim, J.-J. Park, The formability of aluminium sheet in incremental forming, Journal of Materials Processing Technology. 113 (2001) 654–658. Doi:10.1016/S0924-0136(01)00679-3.

[26] Y.H. Kim, J.J. Park, Effect of process parameters on formability in incremental forming of sheet metal, Journal of Materials Processing Technology. 130 (2002) 42–46. Doi:10.1016/S0924-0136(02)00788-4.

[27] J.J. Park, Y.H. Kim, Fundamental studies on the incremental sheet metal forming technique, Journal of Materials Processing Technology. 140 (2003) 447–453. Doi:10.1016/S0924-0136(03)00768-4.

[28] G. Hirt, S. Junk, M. Bambach, I. Chouvalova, Process Limits and Material Behaviour in Incremental Sheet Forming with CNC-Tools, in: Materials Science Forum, 2003: pp. 3825–3830. Doi:10.4028/www.scientific.net/MSF.426-432.3825.

[29] L. Fratini, G. Ambrogio, R. Di Lorenzo, R. Di Lorenzo, L. Filice, F. Micari, Influence of mechanical properties of the sheet material on formability in single point incremental forming, CIRP Annals - Manufacturing Technology. 53 (2004) 207–210. Doi:10.1016/S0007-8506(07)60680-5.

[30] J. Jeswiet, E. Hagan, A. Szekeres, Forming parameters for incremental forming of aluminium alloy sheet metal, Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture. 216 (2002) 1367–1371. Http://sdj.sagepub.com/lookup/10.1243/095440502320405458%5Cnpapers3://publication/doi/10.1243/095440502320405458.

[31] M. Ham, J. Jeswiet, Single point incremental forming and the forming criteria for AA3003, CIRP Annals - Manufacturing Technology. 55 (2006) 241–244. Doi:10.1016/S0007-8506(07)60407-7.

[32] P.A.F. Martins, L. Kwiatkowski, V. Franzen, A.E. Tekkaya, M. Kleiner, Single point incremental forming of polymers, CIRP Annals - Manufacturing Technology. 58 (2009) 229–232. Doi:10.1016/j.cirp.2009.03.095.

[33] G.L. Manco, G. Ambrogio, Influence of thickness on formability in 6082-T6, International Journal of Material Forming. 3 (2010) 983–986. Doi:10.1007/s12289-010-0934-6.

[34] M.B. Silva, L.M. Alves, P.A.F. Martins, Single point incremental forming of PVC: Experimental findings and theoretical interpretation, European Journal of Mechanics - A/Solids. 29 (2010) 557–566. Doi:10.1016/j.euromechsol.2010.03.008.

[35] T.A. Marques, M.B. Silva, P.A.F. Martins, On the potential of single point incremental forming of sheet polymer parts, International Journal of Advanced Manufacturing

Technology. 60 (2012) 75–86. Doi:10.1007/s00170-011-3585-y.

[36] S.P. Shanmuganatan, V.S. Senthil Kumar, Metallurgical analysis and finite element modelling for thinning characteristics of profile forming on circular cup, Materials and Design. 44 (2013) 208–215. Doi:10.1016/j.matdes.2012.07.042.

[37] S. Golabi, H. Khazaali, Determining frustum depth of 304 stainless steel plates with various diameters and thicknesses by incremental forming, Journal of Mechanical Science and Technology. 28 (2014) 3273–3278. Doi:10.1007/s12206-014-0738-6.

[38] I. Bagudanch, M.L. Garcia-Romeu, G. Centeno, A. El??As-Z????Iga, J. Ciurana, Forming force and temperature effects on single point incremental forming of polyvinylchloride, Journal of Materials Processing Technology. 219 (2015) 221–229. Doi:10.1016/j.jmatprotec.2014.12.004.

[39] M. Ham, J. Jeswiet, Forming limit curves in single point incremental forming, CIRP Annals - Manufacturing Technology. 56 (2007) 277–280. Doi:10.1016/j.cirp.2007.05.064.

[40] G. Hussain, L. Gao, N. Hayat, Forming Parameters and Forming Defects in Incremental Forming of an Aluminum Sheet: Correlation, Empirical Modeling, and Optimization: Part A, Materials and Manufacturing Processes. 26 (2011) 1546–1553. Doi:10.1080/10426914.2011.552017.

[41] G. Hussain, H.R. Khan, L. Gao, N. Hayat, Guidelines for Tool-Size Selection for Single-Point Incremental Forming of an Aerospace Alloy, Materials and Manufacturing Processes. 28 (2013) 324–329. Doi:10.1080/10426914.2012.700151.

[42] G. Hussain, L. Gao, Z.Y. Zhang, Formability evaluation of a pure titanium sheet in the cold incremental forming process, International Journal of Advanced Manufacturing Technology. 37 (2008) 920–926. Doi:10.1007/s00170-007-1043-7.

[43] A. Petek, K. Kuzman, J. Kopac, Deformations and forces analysis of single point incremental sheet metal forming, Archives of Materials Science and Engineering. 35 (2009) 107–116. Http://www.archivesmse.org/vol35_2/3527.pdf.

[44] M. Durante, A. Formisano, A. Langella, Observations on the influence of tool-sheet contact conditions on an incremental forming process, Journal of Materials Engineering and Performance. 20 (2011) 941–946. Doi:10.1007/s11665-010-9742-x.

[45] M.B. Silva, P.S. Nielsen, N. Bay, P.A.F. Martins, Failure mechanisms in single-point incremental forming of metals, International Journal of Advanced Manufacturing Technology. 56 (2011) 893–903. Doi:10.1007/s00170-011-3254-1.

[46] G. Centeno, I. Bagudanch, A.J. Martínez-Donaire, M.L. García-Romeu, C. Vallellano, Critical analysis of necking and fracture limit strains and forming forces in single-point incremental forming, Materials and Design. 63 (2014) 20–29. Doi:10.1016/j.matdes.2014.05.066.

[47] G. Ambrogio, L. Filice, F. Micari, A force measuring based strategy for failure prevention in incremental forming, Journal of Materials Processing Technology. 177 (2006) 413–416. Doi:10.1016/j.jmatprotec.2006.04.076.

[48] X. Ziran, L. Gao, G. Hussain, Z. Cui, The performance of flat end and hemispherical end

tools in single-point incremental forming, International Journal of Advanced Manufacturing Technology. 46 (2010) 1113–1118. Doi:10.1007/s00170-009-2179-4.

[49] G. Hussain, L. Gao, N. Hayat, N.U. Dar, The formability of annealed and pre-aged AA-2024 sheets in single-point incremental forming, International Journal of Advanced Manufacturing Technology. 46 (2010) 543–549. Doi:10.1007/s00170-009-2120-x.

[50] K.A. Al-Ghamdi, G. Hussain, Threshold tool-radius condition maximizing the formability in SPIF considering a variety of materials: Experimental and FE investigations, International Journal of Machine Tools and Manufacture. 88 (2015) 82–94. Doi:10.1016/j.ijmachtools.2014.09.005.

[51] M. Strano, Technological representation of forming limits for negative incremental forming of thin aluminum sheets, Journal of Manufacturing Processes. 7 (2005) 122–129. Doi:10.1016/S1526-6125(05)70089-X.

[52] V.S. Le, A. Ghiotti, G. Lucchetta, Preliminary Studies on Single Point Incremental Forming for Thermoplastic Materials, International Journal of Material Forming. 1 (2008) 1179–1182. Doi:10.1007/s12289-008-0191-0.

[53] V. Franzen, L. Kwiatkowski, P.A.F. Martins, A.E. Tekkaya, Single point incremental forming of PVC, Journal of Materials Processing Technology. 209 (2009) 462–469. Doi:10.1016/j.jmatprotec.2008.02.013.

[54] Y. Li, Z. Liu, W.J.T. (Bill. Daniel, P.A. Meehan, Simulation and Experimental Observations of Effect of Different Contact Interfaces on the Incremental Sheet Forming Process, Materials and Manufacturing Processes. 29 (2014) 121–128. Doi:10.1080/10426914.2013.822977.

[55] T. Obikawa, S. Satou, T. Hakutani, Dieless incremental micro-forming of miniature shell objects of aluminum foils, International Journal of Machine Tools and Manufacture. 49 (2009) 906–915. Doi:10.1016/j.ijmachtools.2009.07.001.

[56] G. Ambrogio, F. Gagliardi, Temperature variation during high speed incremental forming on different lightweight alloys, International Journal of Advanced Manufacturing Technology. 76 (2014) 1819–1825. Doi:10.1007/s00170-014-6398-y.