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Experimental and Numerical Investigation of Residual Stresses in Incremental Forming

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Double Sided Incremental Forming (DSIF) is gaining importance over Single Point Incremental Forming (SPIF) due to its ability to form complex geometries and the capability to obtain better accuracies. In the present work, residual stresses are measured in pyramidal components formed using SPIF, DSIF using X-ray diffraction technique. Residual stress development mechanism during SPIF and DSIF is studied using Finite Element Analysis (FEA). Stress development along circumferential and meridional directions are explained using bending and unbending of sheet material taking place around forming tool. It is observed that the residual stresses are compressive on the outer surface and tensile on the inner surface of sheet in both circumferential and meridional directions. In DSIF, supporting tool restricts the unbending of sheet causing the residual stresses to be less compressive on the outer surface and less tensile on the inner surface compared to SPIF. It is also observed that with an increase in tool diameter, spring back increased, hence, meridional residual stress on the outer surface became more compressive and circumferential residual stress on the inner surface became more tensile. Residual stresses in ISF are compared with FEA predictions of conventional stamping process. [doi:10.2320/matertrans.MT-ML2019011]

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1. Introduction

Incremental Sheet Forming (ISF) is a die less sheet forming process, which is used to form complex parts using series of small incremental deformations. In incremental forming, sheet metal is peripherally clamped and simple tools are used to deform the sheet progressively by moving in predefined paths. Formability in ISF is high compared to conventional stamping.[1–5] However, it is desirable to form components with good accuracy and favorable mechanical properties. SPIF is the simplest variant of ISF, which uses only one tool to form the component (Fig. 1(a)). In SPIF, lack of support between component opening and sheet fixture results in unwanted bending at the component opening. This problem can be addressed by another variant of ISF known as DSIF (Fig. 1(b)).[6] In DSIF, in addition to the forming tool, one more tool (moving in synchronization with forming tool) is used to provide local support from the other side of the sheet. Roles of the tools can be changed between forming and supporting to form complex geometries.

Repeated bending and unbending of sheet material around the tools results in residual stress in formed component; affecting its accuracy and properties. Radu *et al.*[7] investigated the effect of process parameters (tool diameter, incremental depth, feed rate and spindle speed) on residual stresses through the thickness in components of SS 304 formed using SPIF. In most of the cases, compressive residual stress existed on the outer surface and tensile residual stress existed on the inner surface (tool contacting side) of the component. They reported that tool feed rate significantly affected the state of residual stress, i.e., when the feed rate is doubled from 1500 mm/min to 3000 mm/min nature of residual stress changed from tensile to compressive in most of the locations along through thickness direction.

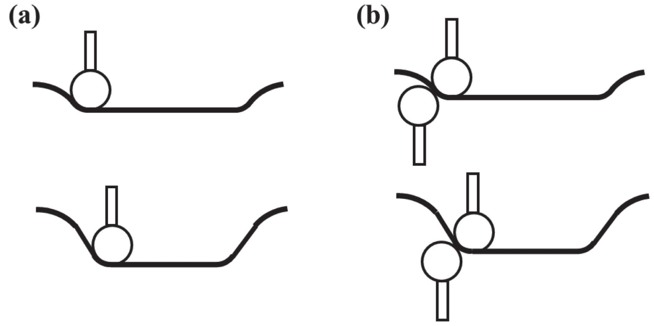

Fig. 1 Incremental sheet forming variants used in present study (a) SPIF (b) DSIF.

Radu *et al.*[8] compared the residual stress in the double frustum of a pyramid with the double frustum of a cone formed using SPIF and concluded that residual stresses in case of pyramid geometry are higher compared to conical geometry and attributed this difference to the presence of high curvature corners in pyramid which acts like stress concentrators. Singh *et al.*[9] studied the surface residual stress distribution in Deformation Machining (DM) process, which is a combination of thin wall machining and SPIF. They have used Nano-indentation technique to measure residual stresses, and reported that compressive residual stresses generated during thin wall machining are more than the tensile residual stresses generated during forming results in compressive residual stresses in final part. Shi *et al.*[10] investigated the state of residual stresses in components formed using SPIF of Cu/Steel bonded laminates. Residual stresses in tool movement and transverse to tool movement directions from the inner side of component (tool contacting side) are measured using hole drilling method. They found that the tool diameter and wall angle have a significant influence on residual stresses compared to spindle rotation, feed rate and incremental depth. They reported that the

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residual stresses are compressive in nature on the inner side and became less compressive with an increase of depth in the thickness direction. Whereas others reported tensile residual stresses on the inner surface.[7,9,12] Bambach *et al.*[11] showed that residual stresses significantly affect the accuracy of the component when it is trimmed after forming using SPIF. They formed a doubly curved free-form geometry at the base of a pyramid and trimmed the unwanted portions to obtain desired part. They measured the geometrical accuracy of formed component after unclamping the formed component from machine fixture. Trimming the component after forming resulted in maximum shape deviation of 37.1 mm. Whereas reducing the residual stresses in the component before trimming by annealing for one hour at 600°C, decreased the maximum deviation to 4.9 mm. Tanaka *et al.*[12] used SPIF to make dental prosthesis component and reported that tensile residual stresses is present on the inner surface and compressive stress on the outer surface. They studied the effect of tool diameter and feed rate on residual stresses in circumferential direction using FEA and reported that tool diameter has significant influence. They used 0.2 mm thickness sheet and 0.5 mm, 1 mm, 2 mm and 4 mm diameter tools and reported that the residual stress on inner side decreased with increase in tool diameter. Jimenez *et al.*[13] investigated the residual stress distribution in SPIF of Al 6061 by X-ray diffraction technique. They measured residual stresses on both inner and outer surfaces of a pyramid frustum with wall angle varying from 45° to 80°. They found that the compressive residual stresses are present on the outer surface at lower wall angle and changed to tensile at higher wall angle (above 58°). In case of the inner surface, residual stresses are tensile at lower wall angle and compressive at higher wall angle. Otsu *et al.*[14] studied the influence of forming temperature, heat treatment and equivalent strain on hardness of pyramidal components of AZ31 magnesium alloy formed using SPIF. Equivalent strain in the component is controlled by repeatedly forming the material in multiple stages. After forming an intermediate geometry, the component is reversed to form from opposite side and obtain the final geometry. They reported that simultaneous control of shape and hardness was possible when the forming and heat treatment temperatures are below recrystallization temperature. Forming pyramids with same equivalent strain (different wall angles) at 100°C and stress relaxation heat treatment at 150°C resulted in same hardness. Whereas forming and heat treating at 200°C resulted in higher hardness for higher major strain component.

To the best of authors' knowledge, the studies on residual stresses in incremental forming are limited to SPIF. Whereas, DSIF is gaining importance over SPIF because of its flexibility to form complex geometries and the capability to obtain better accuracies. Hence, the present work is an attempt to study the residual stresses in both DSIF and SPIF and comparison between them.

2. Methodology

In the present work, stress history at a point on pyramidal component formed using SPIF and DSIF is studied using FE analysis. Residual stresses at selected points are measured

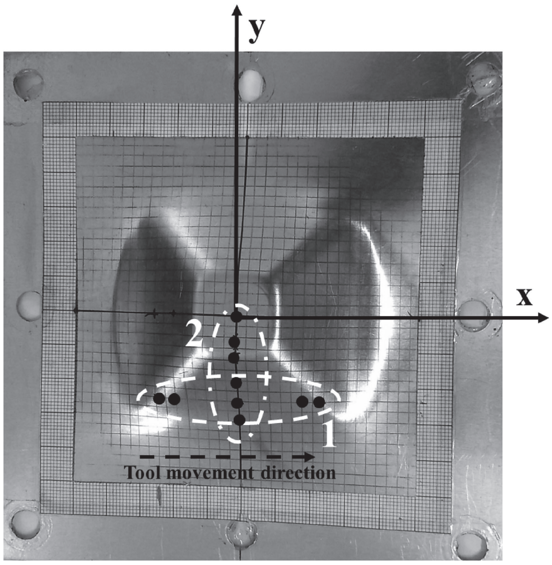

Fig. 2 Measuring points on component (1) Along tool movement direction (2) Transverse to tool movement direction.

using X-ray diffraction technique and compared with FE predictions. The surface of sheet on which forming tool is in contact is referred to as the inner surface and the other surface is referred as the outer surface. A square grid is marked on the sheet before forming (Fig. 2), to identify the location of points where residual stresses are measured on formed component to compare with numerical predictions. Aluminium 5052 sheets of 0.8 mm thickness are used to form the components.

2.1 Measurement procedure

Residual stresses at chosen points on the surface of pyramidal component are measured using X-ray diffraction technique (Proto Manufacturing, MP40P) using $sin^2 \psi$ method. In this method, inter-planar spacing (d) of crystal lattice on the surface is determined using Bragg's law: $n\lambda = 2d\,sin\,\theta$, where λ is the wavelength, θ is the incident angle, n is a positive integer. Residual stress measurement on the sheet before forming the component revealed that the initial

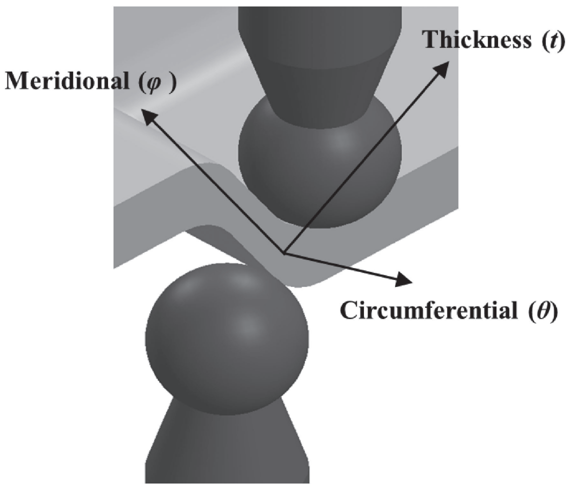

Fig. 3 Principal directions in incremental forming.

residual stresses are uniformly distributed throughout the sheet. Residual stresses on formed components after unclamping are measured along the principal directions on the surface namely meridional (perpendicular to tool movement) and circumferential (along tool movement) directions (Fig. 3). Change of residual stress from initial value is reported in this work. It has to be noted that the directional nature of residual stresses is not presented in earlier studies.[7–9,13)]

2.2 Finite element analysis

To validate the measured residual stresses, implicit finite element simulations of SPIF and DSIF are carried out using Abaqus software. Properties of material (Al 5052) used are: Young's Modulus (E) = 73 GPa, Yield strength (σ_y) = 190.5 MPa and flow curve is given by $\sigma = 412\epsilon^{0.16}$ MPa. During the analysis tool path given to forming tool in both SPIF and DSIF are same. In SPIF, there is no support on outer surface of sheet; whereas in DSIF support is provided throughout the forming on outer surface sheet. The sheet is modelled as deformable body and is discretized using four noded shell elements (S4R) of size 1 mm × 1 mm with reduced integration. Sheet of 100 mm × 100 mm is used with fixed boundary condition (constraining all the translational and rotational degrees of freedom). The forming and supporting tools are modelled as analytical rigid bodies. Contact between tool and sheet is assumed to be frictionless as lubricant is used to minimize the friction during forming. In addition, temperature effects are neglected as special tool design[15)] is used to minimize friction and rise in temperature at the deformation is observed to be not more than 20°C. The sheet material is modelled as elasto-plastic with isotropic hardening. Forming process is modelled in three steps: (1) Forming the geometry (2) Retracting the tool (3) Unclamping the periphery. Stress development is studied during forming the geometry. Residual stress measurement is done after unclamping the component from fixture; hence, comparison with FE predictions is done after releasing the boundary after forming. Residual stress distribution at the end of each step of SPIF is shown in Fig. 4.

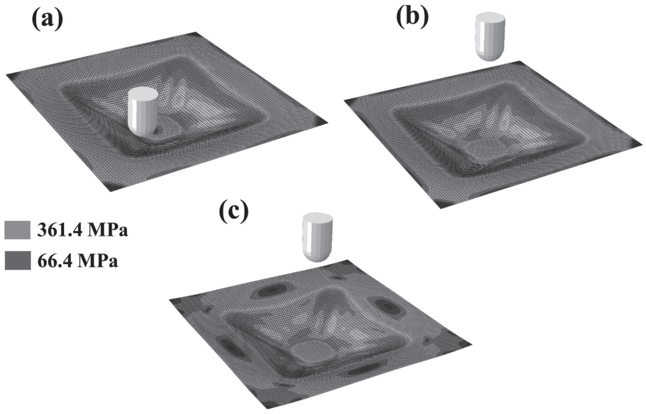

Fig. 4 Residual stresses during ISF (a) End of deformation (b) After tool retract (c) After tool unclamping.

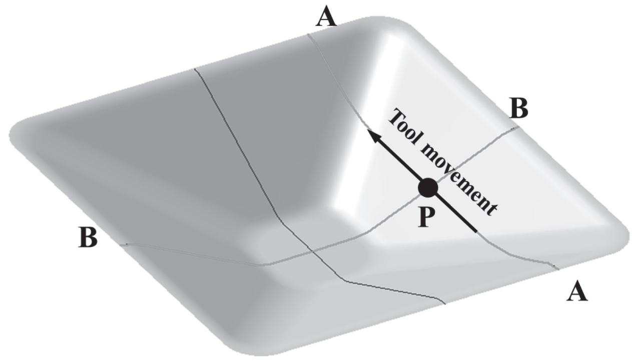

Fig. 5 Cross sectional profiles and tool paths for profile development.

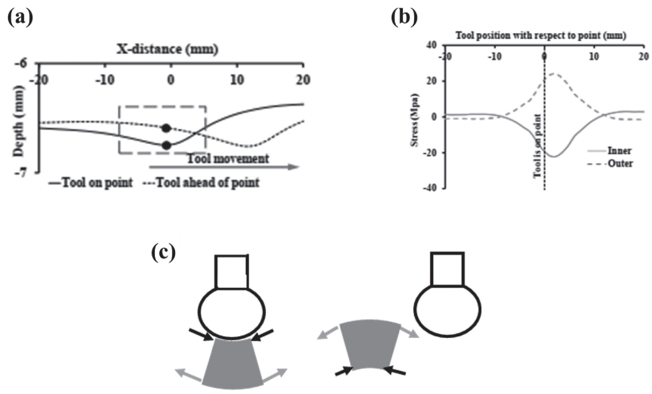

Fig. 6 Profile variation along circumferential direction (section AA) as tool moves on the point (a) Profile variation (b) Stress variation (c) Stress reversal.

3. Results

In ISF, when tool moves over a point P (Fig. 5), bending and unbending of material takes place. Stress development along tool movement direction (circumferential) and meridional direction are explained using bending and unbending phenomena taking place along profiles AA and BB (Fig. 5) observed in FE analysis.

Variation of profile AA and circumferential stress at point P when the tool is at P and moving ahead are shown in Fig. 6(a) and 6(b). It can be seen that the profile at P bends around the tool when the tool is on it and unbending takes place when tool moves ahead. Hence, when the tool is on point P, outer surface is in tension and inner surface is in compression (Fig. 6(c)). When tool moves ahead of point P, un-bending takes place along AA resulting in compressive residual stress on outer surface and tensile residual stress on inner surface in circumferential direction (Fig. 6(c)).

Variation of profile *BB* (meridional direction, Fig. 5) when tool moves in a segment of spiral path (Fig. 7(a)) is shown in Fig. 7(b). The profiles shown in Fig. 7(b) correspond to the tool positions *a* and *b* shown in Fig. 7(a), which are on the opposite sides of tool path. When tool moves from *a* to *b*, profile lifts up due to spring back. To compare the curvature at *P* before and after spring back, the profile when tool is at *b* is translated down. It can be seen that the translated profile is outside the profile when tool is at *a* (Fig. 7(c)). Which implies that unbending took place along *BB* at *P* when tool

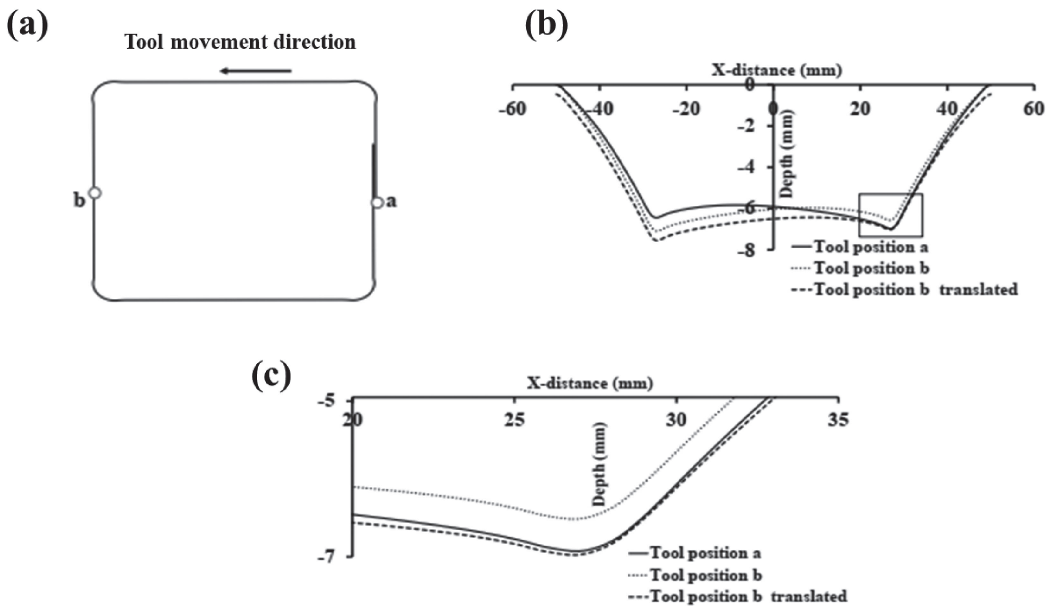

Fig. 7 Profile variation along meridional direction (section BB) as tool moves to diagonally opposite direction (a) Tool position along segment of spiral (b) Bending and unbending (c) Bending and unbending.

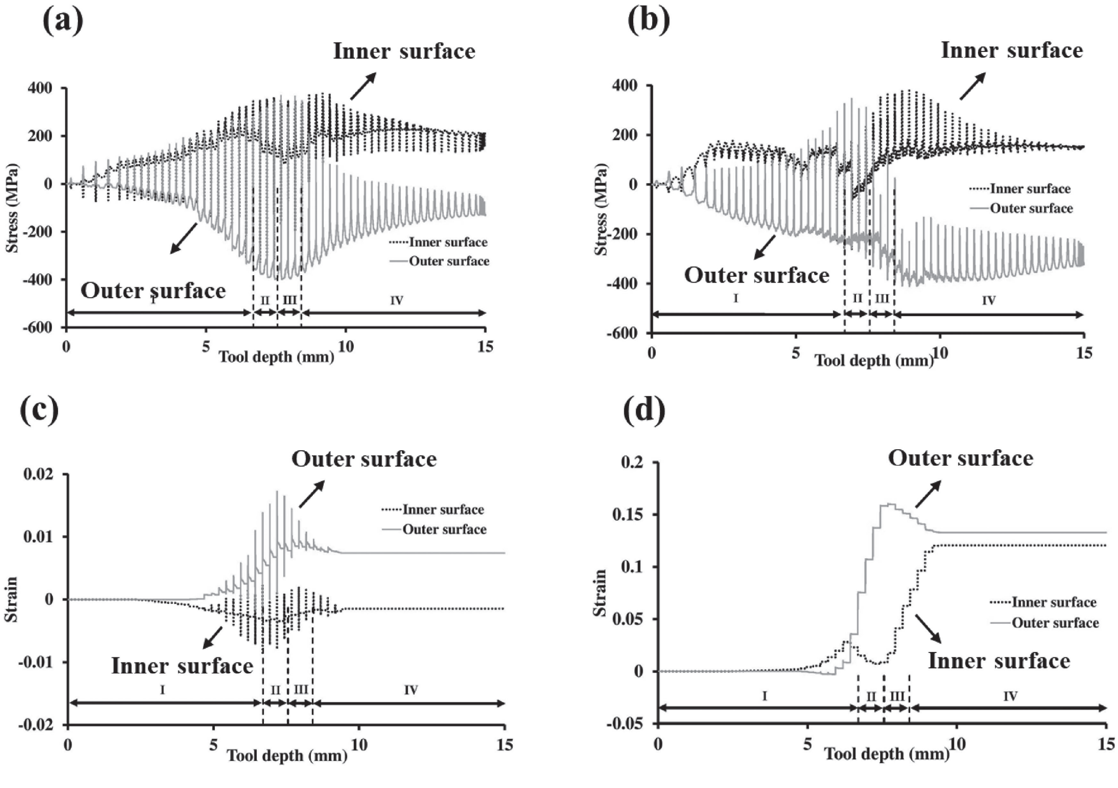

Fig. 8 Stress and strain development in SPIF (a) Circumferential stress (b) Meridional stress (c) Circumferential strain (d) Meridional strain.

moved away from it resulting in compressive residual stress on outer surface and tensile residual stress on inner surface in meridional direction.

3.1 Stress and strain evolution

History of stresses and strains at a point located at the centre of pyramid face (Fig. 5) along circumferential and meridional directions on outer and inner surfaces during SPIF is shown in Fig. 8. Forming time can be divided into four zones based on the location of point *P* with respect to tool (Fig. 9). Initially point P will be in undeformed region of sheet (*zone-I*, Fig. 9(a)). As the deformation progresses, tool moves in depth direction and point *P* comes into the groove region (due to the indentation of tool into sheet and wrapping of sheet around the tool) close to the tool (*zone-II*, Fig. 9(b)). As deformation progresses further, the material at point *P* enters deformation zone (*zone-III*, Fig. 9(c)) and finally reaches to wall/deformed region (*zone-IV*, Fig. 9(d)). Peaks

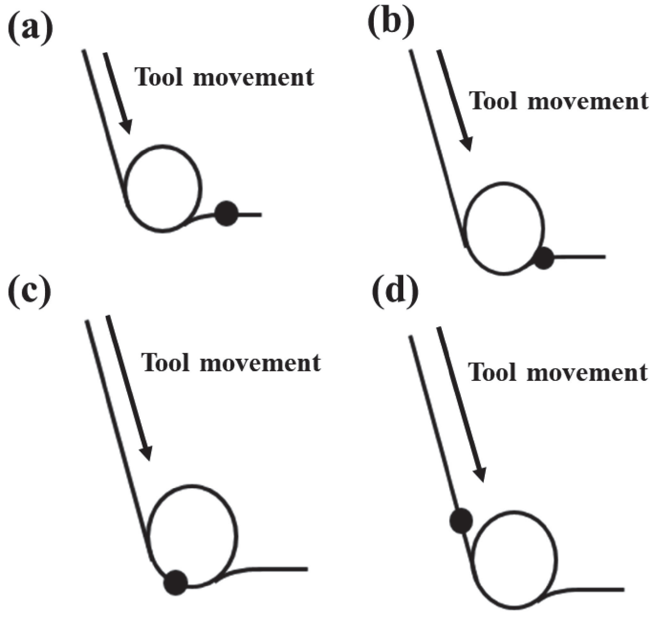

Fig. 9 Various locations of selected point with respect to tool position (a) Zone I (b) Zone II (c) Zone III (d) Zone IV.

observed in stress histories in Fig. 8 (circumferential and meridional stresses on inner and outer surfaces) are when the tool location is close to the selected point in each segment of spiral.

As the tool moves ahead, unbending of the profiles take place in both circumferential and meridional directions (Fig. 6, 7) resulting in compressive residual stresses on the outer surface and tensile residual stresses on the inner surface. In SPIF, residual stress in circumferential direction on outer surface of sheet increased in compression when point is in *zone-I* and became very high in *zones-II* and *III*, where deformation takes place (Fig. 9). From the strain evolution in Fig. 8(c) also it is evident that the material deforms when the point is in *zones-II* and *III*. As the tool progresses in depth direction, relaxation takes place resulting in less compressive residual stress on outer surface. Residual stress in circumferential direction on the inner surface of sheet increased in tension when point is in *zone-I*. In groove region (zone-II), reduction in tensile nature is observed as the front portion of tool pushes the material, which is evident from the negative strain (Fig. 8(c)). In deformation zone (*zone-III*), residual stress increased in tension due to material stretching, which is evident from the increase in strain (Fig. 8(c)).

Residual stress in meridional direction on outer surface gradually increased in compression and on the inner surface it increased in tension in zone-I. On the outer surface, meridional stress is highly tensile in groove region (zone-II), when the tool is close to point P; hence stretching took place in outer surface (Fig. 8(d)). Whereas on the inner surface meridional stress is highly tensile in the deformation zone (zone-III), hence stretching took place in inner surface in zone-III (Fig. 8(d)). In zone-III unbending of material takes place in meridional direction which resulted in reduction of strain in outer surface and stretching in inner surface (Fig. 8(d)). Circumferential strain is very less compared (Fig. 8(c)) to meridional strain (Fig. 8(d)), which shows that plane strain deformation took place.

3.2 Residual stresses

Residual stress in components formed using SPIF and DSIF are measured and compared at the points shown in Fig. 2. Both circumferential and meridional stresses are measured on outer surface, whereas only circumferential stress is measured on inner surface. Meridional stress on inner surface could not be measured as component geometry was obstructing the movement of the X-ray source. Comparison of measured and FEA predicted residual stresses during SPIF and DSIF are shown in Fig. 10.

From both experiments and FEA, it is observed that in SPIF, residual stresses on outer surface in both circumferential and meridional directions are compressive in nature (Fig. 10(a), (b)); Residual stresses on inner surface in circumferential direction are tensile in nature (Fig. 10(a)). Similar observations are reported earlier.[7,9,12] Circumferential and meridional residual stresses on outer surface are compressive at the centre of component, highest in fillet region, which was deformed just before completing the forming process and the compressive nature reduced as moving towards the component opening where relaxation is more as deformation progresses.

In DSIF residual stress trends are observed to be similar to that of SPIF with lower magnitude. Stretching between support and forming tool resulted in lower compressive stress in meridional direction. To study the effect of tool diameter on residual stresses, FE simulations are carried out with tool diameters of 8 mm and 12.7 mm. With increase in tool diameter, significant variation is observed in meridional stress on outer surface (−287.4 MPa for 8 mm and −316.8 MPa for 10 mm).

It can be seen from Fig. 11 that the nature of residual stresses in stamping are same as that of SPIF and DSIF. However, the magnitudes are less in stamping. Comparing the difference between residual stresses on top and bottom surfaces shows that stamping and DSIF have low difference whereas SPIF has high difference. Hence DSIF can be used to form components with residual stresses similar to that of stamping.

4. Conclusion

In the present work, residual stresses on pyramidal components formed using SPIF, DSIF are investigated using X-ray diffraction technique. Residual stress development during SPIF and DSIF is studied using FE analysis. It is observed that the profile variation with tool movement caused bending and unbending of sheet around the tool, when tool moves over it, resulting in compressive residual stresses on outer surface and tensile residual stresses on inner surface of the sheet in both circumferential and meridional directions. It is observed from simulations that spring-back increases with increase in tool diameter. Residual stresses on outer surface are less compressive in DSIF compared to SPIF in both circumferential and meridional directions. Comparison of SPIF and DSIF with stamping showed that the difference of residual stresses on outer and inner surface in

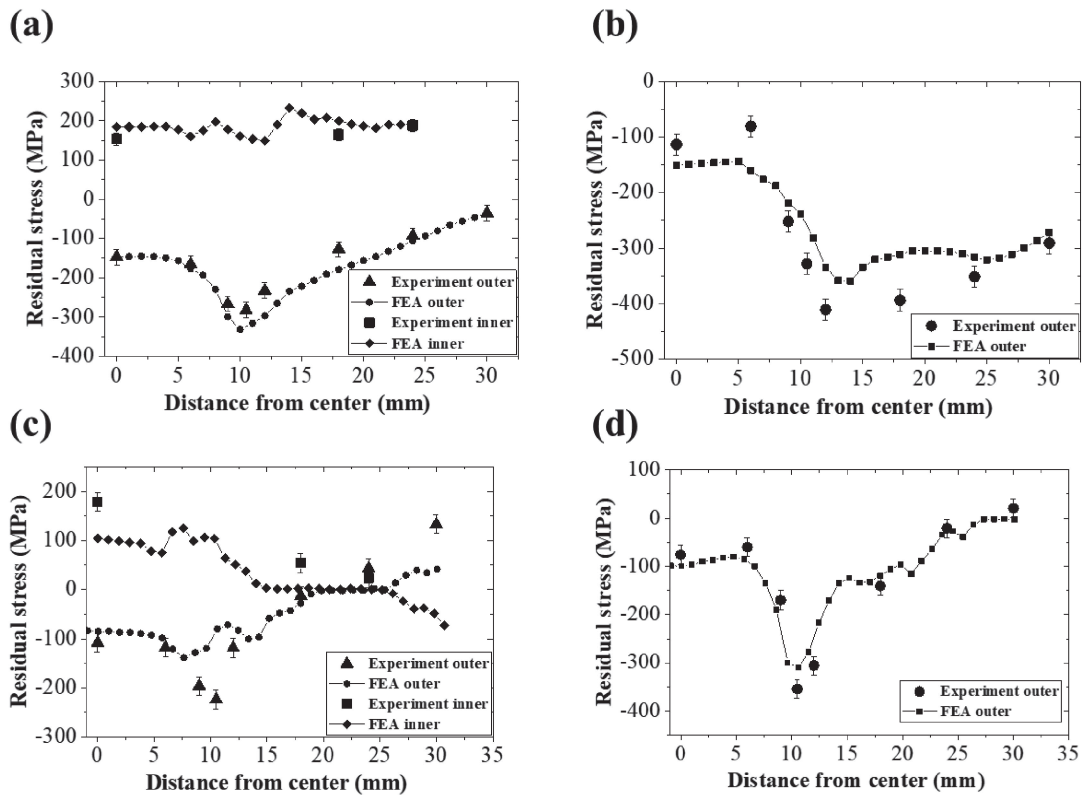

Fig. 10 Residual stresses in SPIF and DSIF (experiments and FEA) (a) SPIF circumferential stress (b) SPIF meridional stress (c) DSIF circumferential stress (d) DSIF meridional stress.

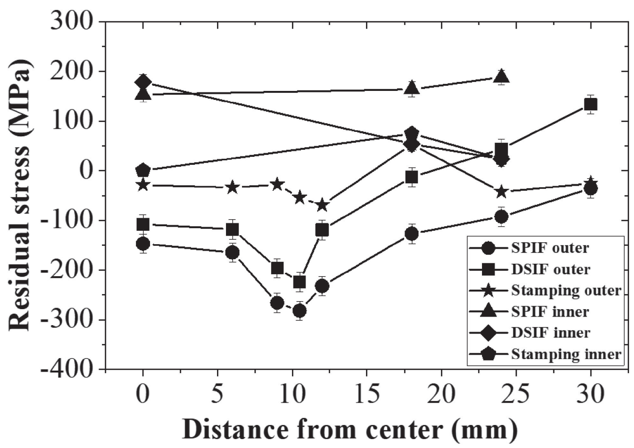

Fig. 11 Comparison of residual stresses between SPIF, DSIF and stamping.

DSIF is close to that of stamping whereas SPIF has higher difference.

Acknowledgments

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REFERENCES

1) J. Jeswiet, F. Micari, G. Hirt, A. Bramley, J. Duflou and J. Allwood: CIRP. Ann. Manuf. Technol. **54** (2005) 88–114.
2) J. Cao, Y. Huang, N.V. Reddy, R. Malhotra and Y. Wang: Proc. 9th Int. Conf. on Technology of Plasticity, (Gyeongju, Korea, 2008) pp. 751–752.
3) N.V. Reddy, R. Lingam and J. Cao: *Incremental Sheet Metal Forming Processes*, (Handbook of Manufacturing Engineering and Technology, Springer) (2014) pp. 411–452.
4) W. Emmens, G. Sebastiani and A. Van den Boogaard: J. Mater. Process. Technol. **210** (2010) 981–997.
5) D. Seong, M. Haque, J. Kim, T. Stoughton and J. Yoon: Int. J. Solids Struct. **51** (2014) 2840–2849.
6) R. Lingam, S. Amit and N.V. Reddy: J. Manuf. Sci. Eng. **138** (2016) 091008.
7) C. Radu, C. Tampu, I. Cristea and B. Chirita: Mater. Manuf. Process. **28** (2013) 572–576.
8) C. Radu, E. Herghelegiu, C. Tampu and I. Cristea: Appl. Mech. Mater. **371** (2013) 148–152.
9) A. Singh and A. Agrawal: J. Mater. Process. Technol. **225** (2015) 195–202.
10) X. Shi, G. Hussain, S.I. Butt, F. Song, D. Huang and Y. Liu: J. Manuf. Process. **30** (2017) 14–26.
11) M. Bambach, B.T. Araghi and G. Hirt: Prod. Eng. Res. Devel. **3** (2009) 145–156.
12) S. Tanaka, T. Nakamura, K. Hayakawa and K. Motomura: Proc. 9th Int. Conf. on Numerical Methods in Industrial Forming Processes, (Porto, Portugal, 2007) pp. 775–780.
13) I. Jiménez, C. López, O. Martinez-Romero, P. Mares, H. Siller, J. Diabb, J.A. Sandoval-Robles and A. Elías-Zúñiga: Int. J. Adv. Manuf. Technol. **91** (2017) 2571–2580.
14) M. Otsu, Y. Kai and K. Takashima: Mater. Trans. **49** (2008) 1124–1128.
15) A. Bhattacharya, K. Maneesh, N.V. Reddy and J. Cao: J. Manuf. Sci. Eng. **133** (2011) 061020.