Robust Die Design with Spiral-shape Cavity

K.H. Jung, Y.B. Kim, Y.H. Kim, and G.A. Lee#

***Abstract*—**Scroll compressors are used for air conditioning system in automobiles due to its relatively low pressure loss and vibration, and light-weight. Usually, forging process to manufacture the orbiting scroll, the main component of the scroll compressor, requires high-level technique since the severe cracking at the fixed end of the spiral cavity, which is similar to a wound cantilever beam, can occur. A vertically opened die structure was manufactured and experimentally verified. To overcome the inevitable structural weakness of the spiral cavity, an effective approach in terms of costs was necessary. In this study, finite element analysis is conducted to find out the reason for the cracking of the vertically opened cavity, and a novel design to avoid stress concentration and vertical deflection, causing serious damage to the die, is suggested.

***Keywords*—**Scroll, Die design, Closed die forging, Backpressure, Finite element method

I. Introduction

SCROLL compressor is used for HVAC (Heating, Ventilation, and Air-conditioning) systems of automobiles and small buildings since it has merits in energy efficiency, steady torque requirement due to continuous flow of refrigerant, and less noise and vibration compared to reciprocating compressors [1].

The core component of scroll compressors is the orbiting scroll shown in Fig. 1(a). Due to its complex shape, manufacturing processes based on die casting [2], powder forging [3], and welding a plate and a spiral part [4] have been suggested.

It is not easy to apply metal forming technology to the orbiting scroll due to asymmetric spiral-shape wrap although introducing metal forming can substantially improve the productivity. More specifically, a serious variation in the final height of the spiral-shape wrap was expected according to FEA (Finite Element Analysis) as shown in Fig. 1(b). The non-uniform height distribution causes a waste of material during sequential CNC machining, and increases manufacturing costs after all. Regarding to uniformity in wrap height, other researchers proposed a forging process using back-pressure to obtain more uniform height of wrap [5].

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In this study, forging experiments were carried out with the dies designs, which are available in the literature [5-7], and their reliability was verified experimentally and numerically. Finally, a new approach to improve the stiffness of dies for forging the orbiting scrolls is suggested.

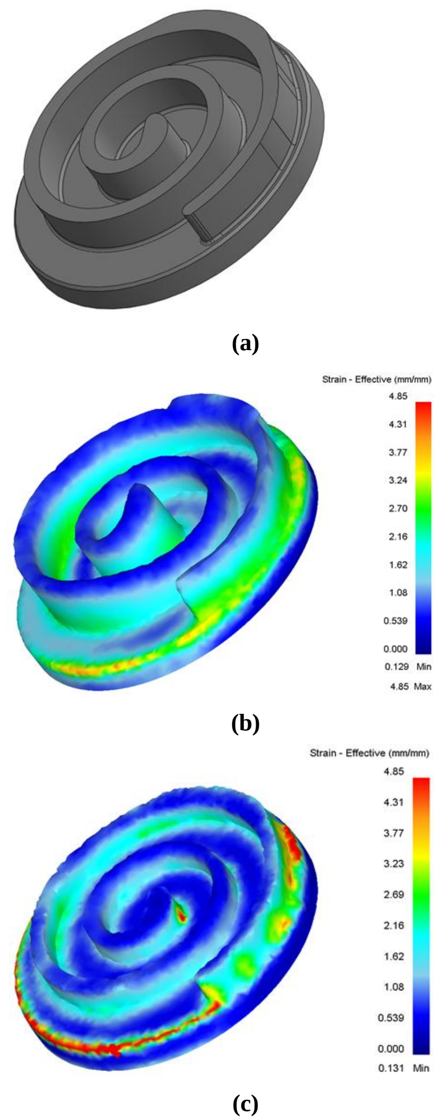


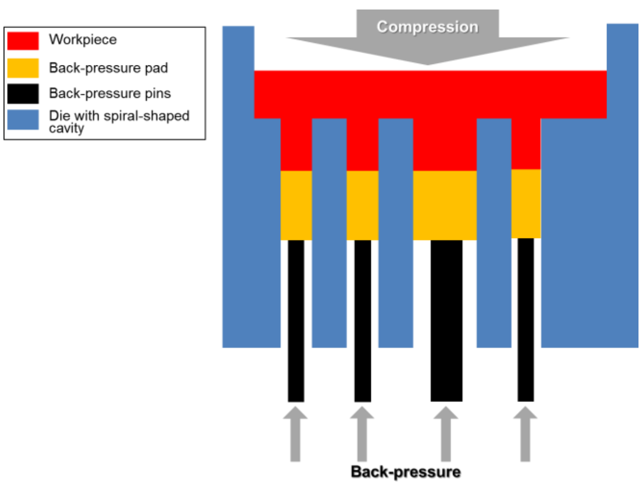
Fig. 1 (a) Orbiting scroll and (b) FE analysis of the orbiting scroll forged without backpressure and (c) forged with backpressure

II. Experiment with Conventional Die Design

The schematic cross-section of the conventional die design, available in the literature, is depicted as shown in Fig. 2(a). The lower die has a vertically opened spiral-shape cavity only. In other words, a wound cantilever beam composes the spiral-shape cavity. The pins, pushing up the spiral-shape pad, are inserted to give upward back-pressure during the upper punch press the material.

A set of dies to carry out forging experiment was manufactured based on the die design with the vertically opened cavity as shown in Fig. 2(b). A billet, 102 mm in diameter and 1000 mm in length, was machined off to prepare the workpieces. Those workpieces were heated up to 350 ℃ in a box furnace. The die cavity, on the other hand, was heated up to 150 ℃ by a torcher.

After the third stroke, a severe crack was found at the end of the spiral, corresponding to the fixed end of a wound cantilever beam, as shown in Fig. 3. Additional one more stroke completely tore the cracked location apart. Thus, it was concluded that the weakness of the vertically opened spiral-shape cavity had to be improved, and FEA was utilized to find a reasonable solution satisfying robustness and costs at the same time.



(a)

(b)

Fig. 2 Scroll forging experiment with vertically opened cavity (a: schematic of die design, b: experiment)

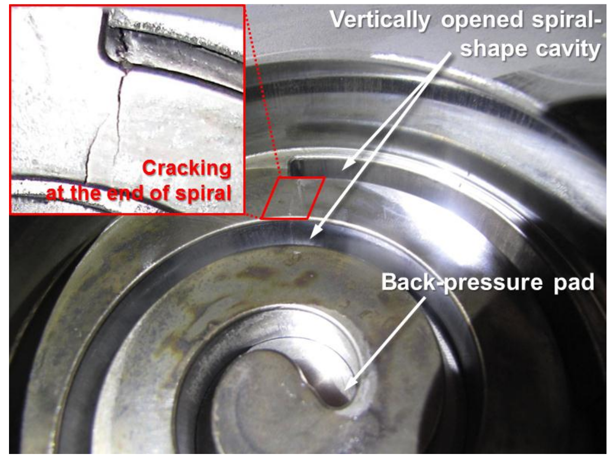


Fig. 3 Cracking at the end of the spiral-shape cavity

III. FE Analysis of Vertically Open Cavity

A three dimensional model of die, 200 mm in diameter and 80 mm in height, for FE analysis was generated with 60000 tetrahedral mesh, and velocity boundary conditions at the outer bottom was given to maximize deflection of the die as shown in Fig. 4. In general, dies are assumed to be a rigid body for simplicity and to reduce time consumption. Those were, however, assumed to be plastically deformable material in this study.

The stress-strain curves of the die material (AISI H13) shown in Fig. 5, included in the material database of FEM software DEFORM v10.0. The shear friction model was used with a shear friction factor of 0.7.

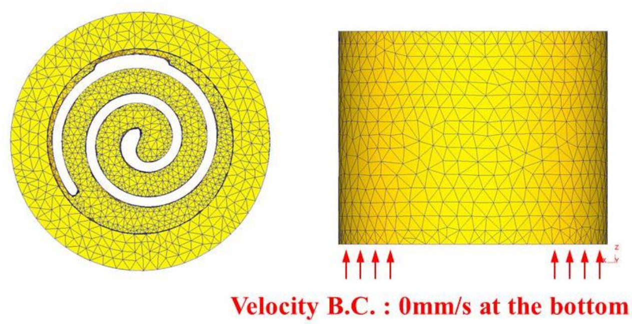


Fig. 4 Die model of vertically opened cavity for FE analysis

In Fig. 6, the numerically obtained results of the vertically opened spiral-shape cavity are shown. Fig. 6(a) shows the vertical displacement of the spiral-shape cavity. According to this figure, the maximum deflection reached -7.0 mm at the stroke 9.0 mm, and a torsional moment was applied to the cavity due to the fixed end.

Figs. 6(b)-(d) show other state variables such as effective stress, effective strain, and Cockroft-Latham damage value. Based on all the results shown in Fig. 6, it was naturally concluded that the fixed end is the most critical weak point as validated by the cracking location in the forging experiment.

http://dx.doi.org/10.15242/IIE.E1213039

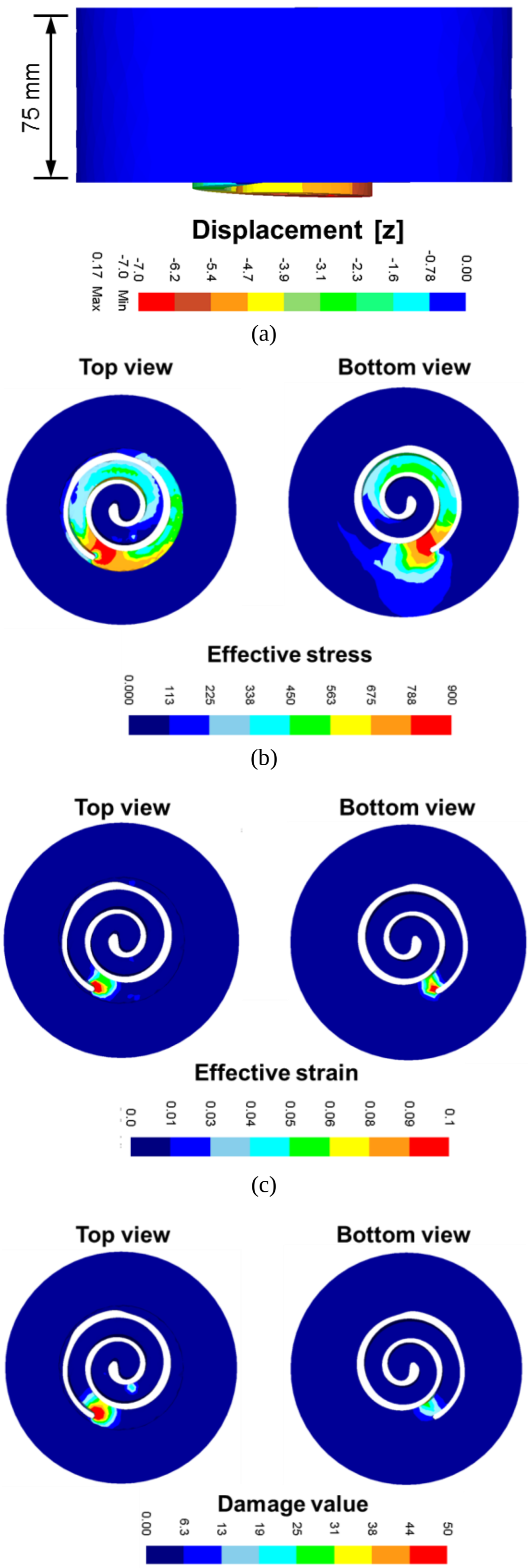


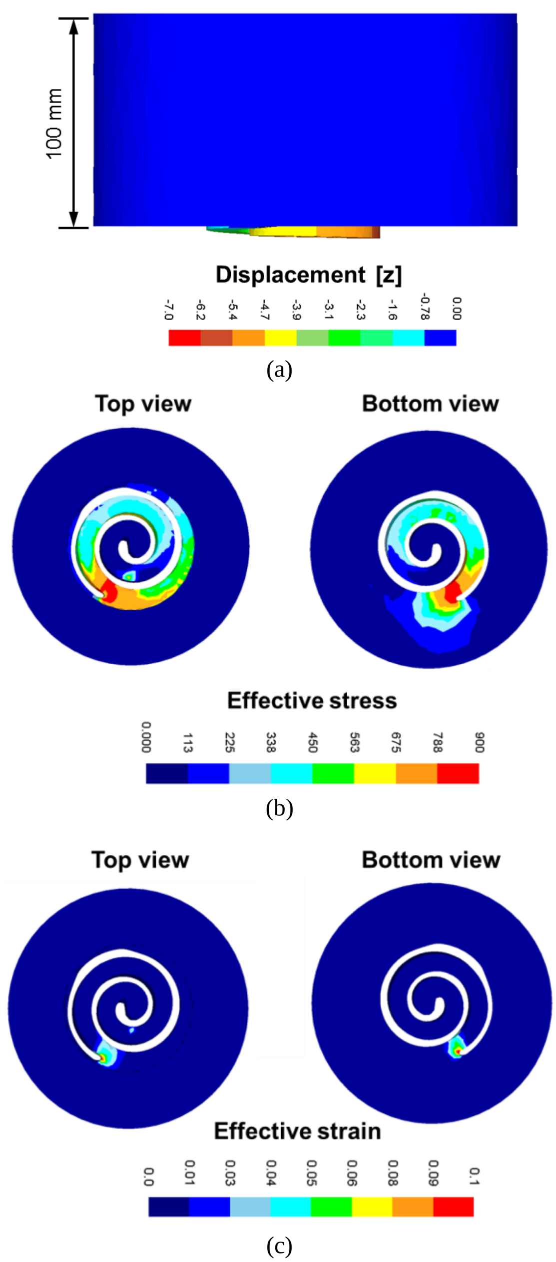
Fig. 6 FE analysis of the die, 75 mm in height, with the vertically opened: (a) vertical displacement, (b) effective stress, (c) effective strain, and (d) damage value at the stroke 9.0 mm

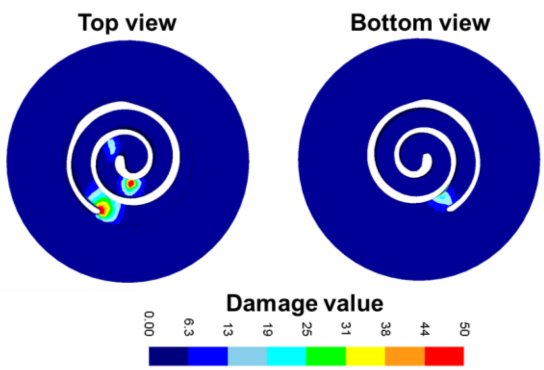
IV. Effect of Die Height

One of the easiest approaches to reinforce the fixed end might be increasing the height of the die with open cavity. The height was increased to be 100 mm and 120 mm as shown in Figs. 7 and 8, respectively.

By increasing the height up to 100 mm and 120 mm, the maximum vertical displacement was slightly reduced to be -6.0 mm and -6.3 mm, respectively. However, concentration of stress, strain, and damage value were still remained. Thus, it was concluded that simply increasing the thickness of the die was not an appropriate or effective approach.

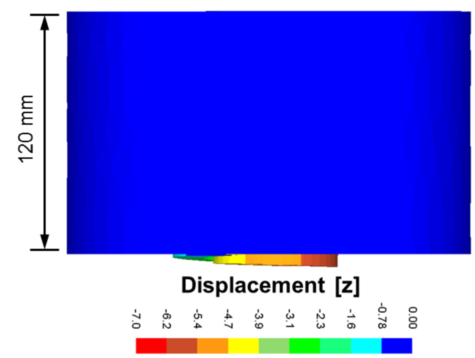
As another approach, high strength materials like tungsten carbide can be considered. However, those materials have less toughness, which is more important rather than strength in this case, and are not advantageous in terms of costs also.



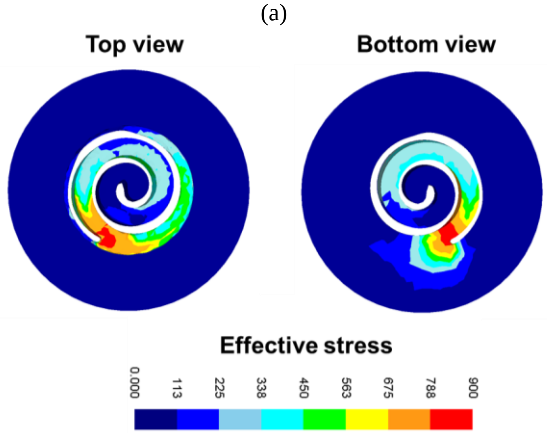


(d)

Fig. 7 FE analysis of the die, 100 mm in height, with the vertically opened cavity: (a) vertical displacement, (b) effective stress, (c) effective strain, and (d) damage value at the stroke 9.0 mm



(a)



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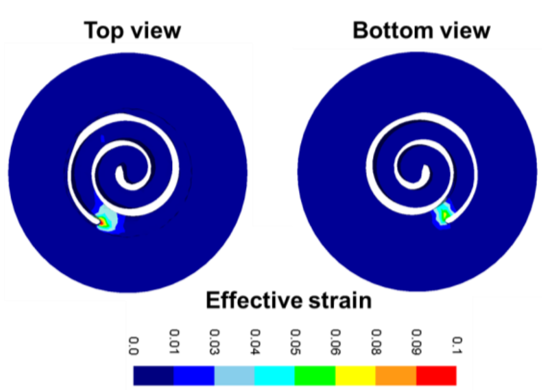
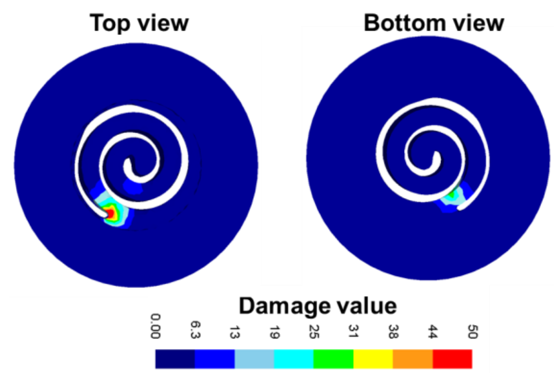


(c)



(d)

Fig. 8 FE analysis of the die, 120 mm in height, with the vertically opened: (a) vertical displacement, (b) effective stress, (c) effective strain, and (d) damage value at the stroke 9.0 mm

V. New die design with vertically closed cavity

In designing die to forge the spiral-shape, two different requirements should be satisfied: prevention of vertical displacement and stress concentration at the fixed end. Therefore, a closed cavity as depicted in Fig. 9 was newly developed in this study. The bottom of the cavity was closed to prevent the vertical displacement. As results, the moving distance of the back-pressure pad was limited, and the height of the die was increased as much as the bottom thickness

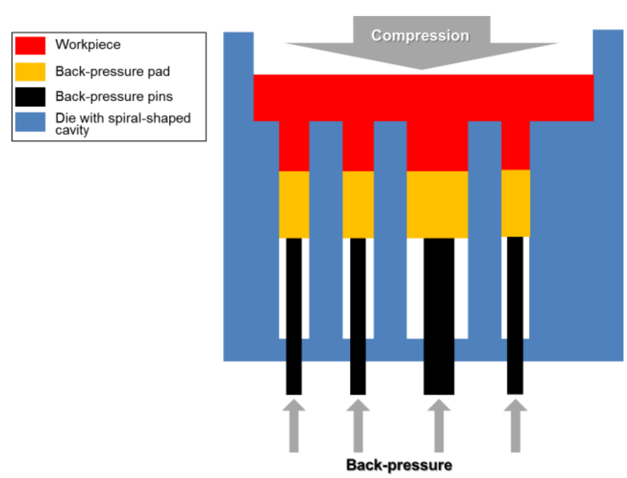


Fig. 9 Die design with vertically closed spiral-shape cavity

To verify the new die design, FE analysis was conducted with the same condition as shown in Figs. 10 and 11. When the cavity was closed, the stress and strain distribution became relatively uniform. By adding the bottom with 15 mm thickness only, the maximum value of vertical displacement on the bottom was -1.5 mm compared to -7.0 mm of the open cavity. Thus, a simple modification of die design was found to be more effective, and to minimize die manufacturing cost.

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A further investigation on optimizing the bottom thickness and experimental verification will be carried out as future works.

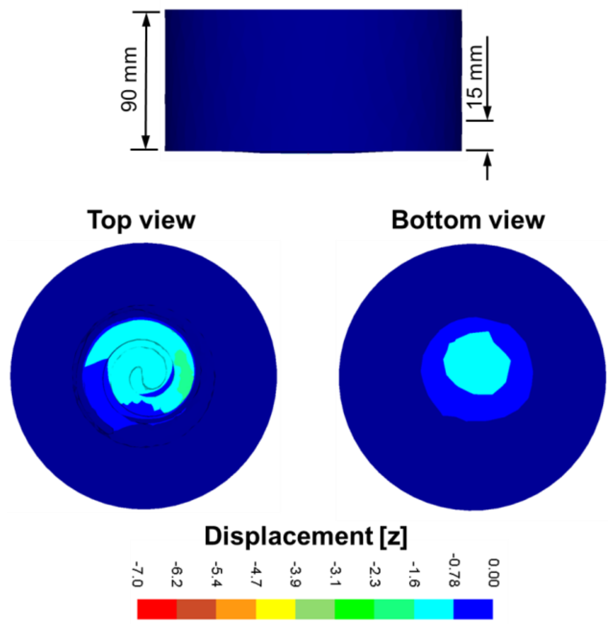
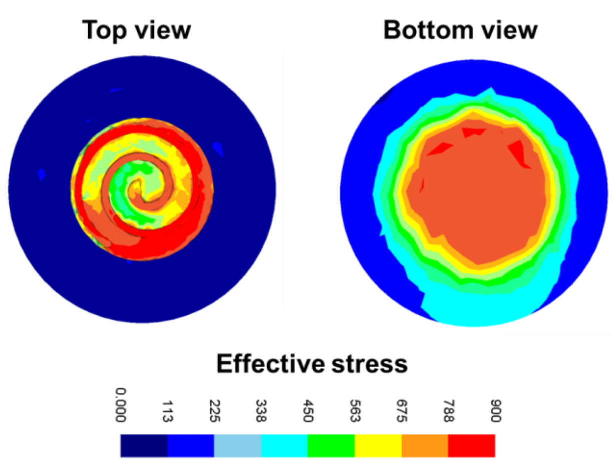
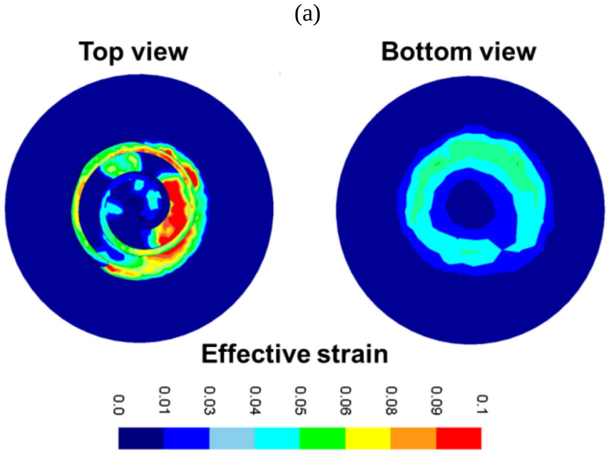


Fig. 10 Vertical displacement of vertically closed cavity



(a)



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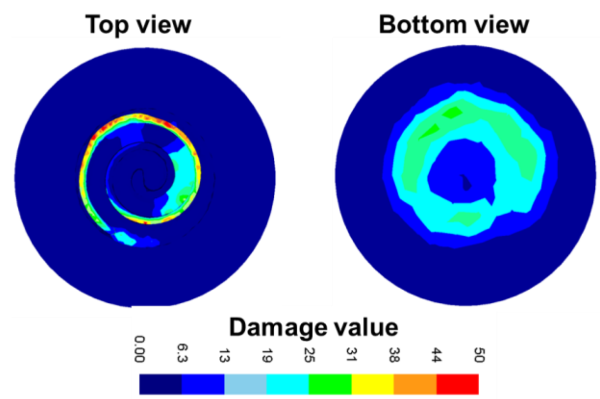

(c)

Fig. 11 FE analysis of the die, 100 mm in height, the vertically closed cavity: (a) effective stress, (b) effective strain, and (c) damage value at the stroke 9.0 mm

VI. CONCLUSION

In this study, it was found out that the die design with the vertically opened spiral-shape cavity, suggested in references, was not applicable in reality since a severe cracking at the fixed end of the spiral occurred.

Using FE analysis, increasing die height was concluded to be ineffective to avoid concentration of stress, strain, and damage value at the fixed end. As a simple and cost-effective approach, newly developed vertically closed spiral-shape cavity was proposed, and was numerically validated in this study.

ACKNOWLEDGMENT

This work was supported by a grant (B551179-11-02-00) from the co-operative research project funded by the Ministry of Knowledge Economy, South Korea.

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