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A study on chevron crack formation and evolution in a cold extrusion †

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Abstract

A numerical algorithm based on the element deletion method and rigid-viscoplastic finite element approach depending on Cockcroft-Latham and specific plastic work fracture criteria was applied to predict formation and evolution of possible cracking in a cold extrusion of aluminum and steel alloys. The Cockcroft-Latham fracture criterion induced an internal crack while an external crack occurred owing to the specific plastic work criterion in simulations. As a result, the Cockcroft-Latham criterion was found to be valid for predicting chevron cracking in comparison with the experimental observation available in the literature. Using the Cockcroft-Latham criterion, cracking was carefully investigated in terms of the size of the crack and gap distance between cracks depending on the number of elements and boundary condition at the punch interface. The critical damage values for the Cockcroft-Latham fracture criterion were also calculated based on the tensile instability and fracture conditions to investigate their effect on possible cracking. Finally, a processing map based on the Cockcroft-Latham fracture criterion for preventing chevron cracking in the cold extrusion of commercially available steel alloy was developed by considering processing parameters such as reduction in area and semicone angle. According to this investigation, the developed element deletion method with the Cockcroft-Latham fracture criterion was reasonably accurate for carrying out chevron cracking analyses in the cold extrusion with proper selection of a critical damage value.

Keywords: Chevron crack; Critical damage value; Element deletion method; Extrusion; Fracture criteria

1. Introduction

Chevron cracks or central bursts are encountered in a cold extrusion or drawing process. Such internal cracks or chevron cracks are difficult to detect and easily cause severe problems in the final products. In producing a large number of stepped shafts with extrusion in the automobile industries, it is important to understand how to prevent the occurrence of chevron cracks during the process. Thus, prediction of chevron cracking is an important issue in the process design and control.

To predict internal cracking like chevron cracking, a study on fracture criteria is essential. Hence, early investigations for the fracture analysis were concentrated on determination of fracture criteria and prediction of crack initiation based on energy criteria. Freudenthal [1] used an effective stress for stress component and Cockcroft and Latham [2] employed a maximum principal stress to calculate the energy term. These criteria were applied and compared for various processes which were simple upsetting, axi-symmetric extrusion, and strip compression and tension by Clift et al. [3], two different preforming processes of upsetting and forward extrusion by Wifi et al. [4], and three sequential stages for manufacturing axi-symmetric pin by Kim et al. [5]. According to these works, prediction of cracking positions for each investigated process was reasonable with the specific plastic work and Cockcroft-Latham criteria, but no unique solution was available for general applications. Thus, determination of proper fracture criterion is necessary to analyze chevron cracking in cold extrusion.

The first attempt to predict occurrence of chevron cracking was made by Avitzur [6] depending on the die angle and reduction of area. Zimmerman et al. [7] experimentally showed that a safe region consists of small die angle and high reduction in area. Zimmerman and Avitzur [8] suggested a criterion for central bursting according to their analytical work based on the upper bound method. For the numerical investigation, Aravas [9] studied the behavior of micro-voids nucleated during an axi-symmetric extrusion with two different die designs. Saanouni et al. [10] applied continuum damage mechanics to thermo-elastoplastic finite element (FE) program and predicted crack formation in cold extrusion. McVeigh and Liu [11] used micro mechanical cell modeling technique and predicted the occurrence and position of chevron crack in extrusion and edge crack in rolling.

The element deletion method is one of the simplest methods

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that can simulate fracture problems within the framework of the finite element method without complicated modifications [12, 13]. There is no need to explicitly represent strong discontinuities in displacement fields since fracture is modeled by a set of deleted elements. Alsos [14] investigated the effect of the element deletion and separation method for mode I tearing and plate cutting in terms of energy dissipation and load aspects. Ceretti et al. [15] applied finite element simulation using element deletion method for orthogonal machining.

In this study, a numerical algorithm based on the element deletion method and rigid-viscoplastic finite element approach was applied for the chevron cracking analysis. Cockcroft-Latham and specific plastic work fracture criteria were applied to predict formation and evolution of possible cracking of aluminum alloy of AA6061. Since the evolution of chevron cracks was also affected by simulation conditions, the cracking phenomenon of commercially available steel introduced in the literature [10] was investigated in terms of the size of the crack and gap distance between cracks by varying the number of elements and boundary condition at the punch interface. In addition, the simulation results were compared to the experimental observation available in the same literature [10]. To decide the critical damage value of the Cockcroft-Latham fracture criterion, instability and tensile fracture conditions were considered to better predict the experimental observations. Finally, a processing map based on the Cockcroft-Latham fracture criterion to prevent chevron cracks in the cold extrusion of the same steel was developed by considering process parameters such as reduction in area and semicone angle.

2. Fracture analysis based on the element deletion method

To carry out the analysis of chevron cracking, a suitable fracture criterion should be determined first. Thus, specific plastic work and Cockcroft-Latham criteria were applied and compared in the current study as follows:

$$\int_0^{\bar{\varepsilon}_f} \bar{\sigma} d\bar{\varepsilon} = C_1 \tag{1}$$

$$\int_0^{\bar{\varepsilon}_f} \sigma_1 d\bar{\varepsilon} = C_2 \tag{2}$$

Here, $\bar{\sigma}$ is the effective stress, σ_1 is the largest tensile principal stress and $\bar{\varepsilon}_f$ is the effective strain at the initial cracking. C_1 and C_2 represent the critical damage value of each criterion in MPa, respectively, depending on the material. Additionally, the critical damage value was determined by two conditions, instability and tensile fracture in the present investigation. For the instability condition, a stress-strain curve that can be represented by $\bar{\sigma} = K\bar{\varepsilon}^n$ in MPa was integrated until the strain at $\bar{\varepsilon}_f = n$ where n is the strain hardening coefficient of the material. For the tensile fracture condition, it was calculated up to the $\bar{\varepsilon}_f$ equal to tensile fracture strain.

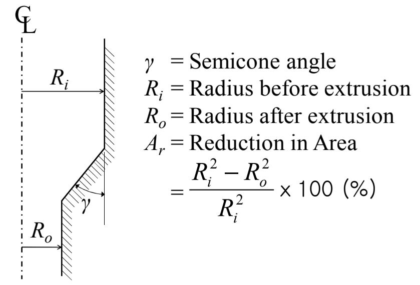

Fig. 1. Main processing parameters investigated in extrusion.

To investigate internal cracking, an in-house fracture analysis program, which was developed by Lee et al. [16], was used. In this program, the element deletion method was applied to the in-house FE program CAMPform-2D which was developed by Kim and Im [17] based on the rigid-viscoplastic constitutive model by adopting two dimensional auto remeshing scheme [18]. According to this approach, a damage value depending on the fracture criteria represented by Eqs. (1) and (2) should be calculated at every time step of deformation during the forming analysis. Comparison between the elemental damage value, which was determined by either Eq. (1) or (2) by introducing the elemental effective strain for $\bar{\varepsilon}_f$ in both equations, and critical damage value depending on the fracture criterion determines which elements should be deleted at the current deformation step. If element deletion does not occur, forming simulation for the next time step continues. When the element deletion occurs, information of the current mesh system including the candidate element to be deleted needs to be transferred to the element deletion routine.

In the element deletion routine, candidate elements were deleted and elements were renumbered for reducing a computation time. By introducing the new mesh layout and boundary conditions, forming simulation is continued for the next time step until the occurrence of next element deletion or the end of simulations.

To find the proper fracture criterion, an aluminum alloy of AA6061 was selected for the testing material because a chevron crack was found in the work of Komori [19]. In the present numerical investigation, the material property was taken as $\bar{\sigma} = 190\bar{\varepsilon}^{0.21}$ MPa from the same reference. Semicone angle and reduction in area as shown in Fig. 1 were selected as processing parameters in a cold extrusion. Initial radius, semicone angle and reduction in area used were 20 mm, 26° and 36%, respectively. According to the work in references [10, 20, 21], shear friction factor was assumed to be 0.1 for simulations with 1 mm/s of punch speed and the total number of quadrilateral elements used was 3700. Axi-symmetric boundary conditions were applied in the present simulation.

In Fig. 2, the distributions of maximum principal stress, effective strain, and effective stress before cracking are given. According to this figure, locations of the maximum values for each component are different. Maximum value of the principal stress occurred at the center of the specimen and the others were concentrated at the corner of the specimen's surface as

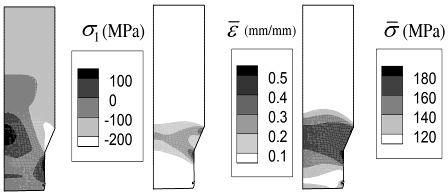

Fig. 2. Distributions of (a) the maximum principal stress, (b) the effective strain, and (c) the effective stress.

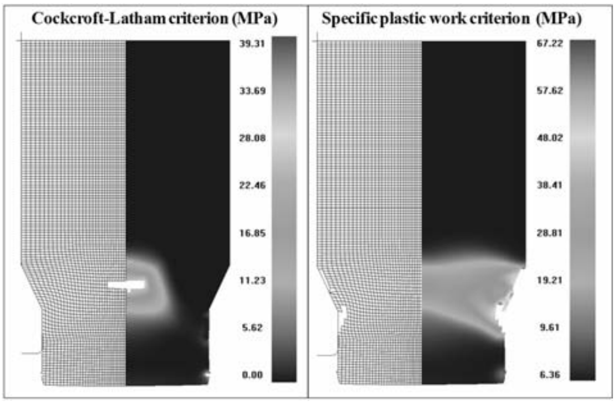

Fig. 3. Crack initiation depending on two different fracture criteria: (a) the Cockcroft-Latham and (b) specific plastic work criterion.

shown in this figure. Thus, distributions of two fracture criteria and the position of crack initiation were distinguished clearly by applying the element deletion method as shown in Fig. 3. According to this figure, the Cockcroft-Latham fracture criterion was more reasonable to predict internal cracking and evolution of chevron cracks as shown in Fig. 4. Therefore, the Cockcroft-Latham criterion was selected for prediction of chevron cracking in the following.

3. Analysis of chevron cracking in cold extrusion

According to the element deletion method, chevron crack formation and evolution were affected by the element mesh size. Thus, it is necessary to investigate the effect of element size and find a proper element size for applications. The size of elements was varied by changing the total number of elements used for the same specimen.

In the simulation, the material was commercially available steel with flow stress of $\bar{\sigma} = 475\bar{\varepsilon}^{0.1}$ MPa according to the work in reference [10]. Initial radius, semicone angle and reduction in area were 25 mm, 18° and 36%, respectively. Shear friction factor of 0.1 was selected from the guideline available in references [10, 20, 21] and the number of elements was varied as shown in Fig. 5. In addition, axi-symmetric boundary conditions were applied with 1 mm/s of punch speed at room temperature.

Crack configurations were similar for all simulation cases as shown in Fig. 5. However, the number of cracks and the ratio

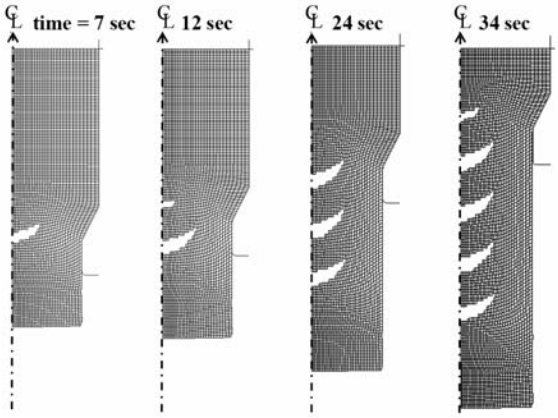

Fig. 4. Chevron crack formation and evolution due to the Cockcroft-Latham criterion after the extrusion began.

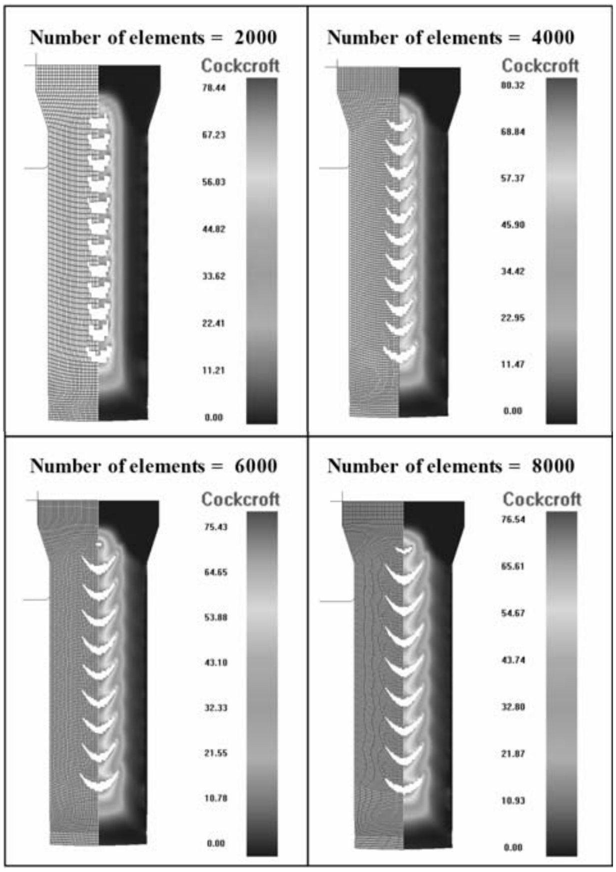

Fig. 5. Distribution of chevron cracks depending on the number of elements.

of cracking area to the entire area of the specimen are changed as plotted in Fig. 6. The number of cracks was varied from 12 to 9 and the ratio of cracking area was also reduced from 8.3% to 5.3% by increasing the number of elements. The number of cracks and the ratio of cracking area were converged to 9 and 5.3% for the 8000 or more elements and for the element size of 0.59 mm or smaller, respectively. Therefore, an element length had to be smaller than 0.0236 times the initial radius of

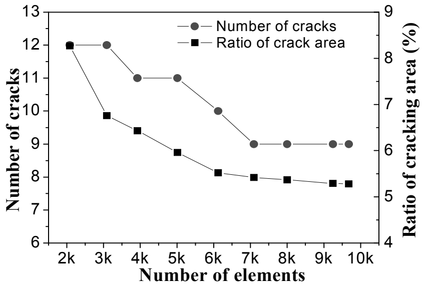

Fig. 6. Change of the number of cracks and the ratio of cracking area.

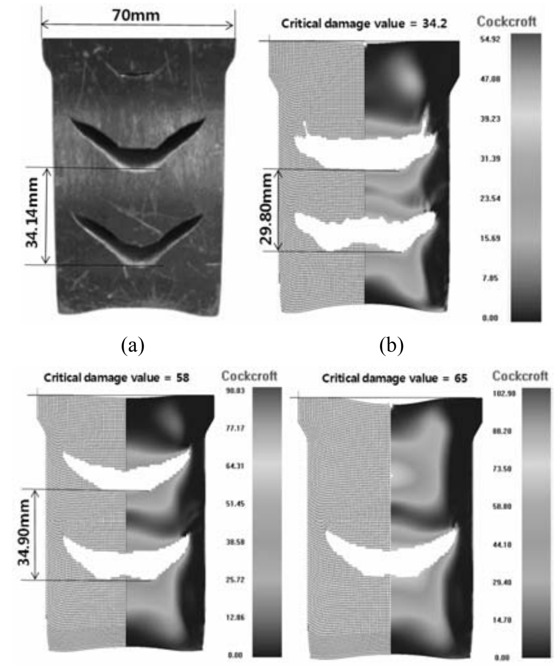

Fig. 7. Comparison of chevron cracks between (a) the experimental (Saanouni et al., [10]) and simulation results by allowing separation of the specimen from the punch due to (b) the instability condition, (c) the tensile fracture condition and (d) the higher critical damage value condition. The dimension of the critical damage value is in MPa.

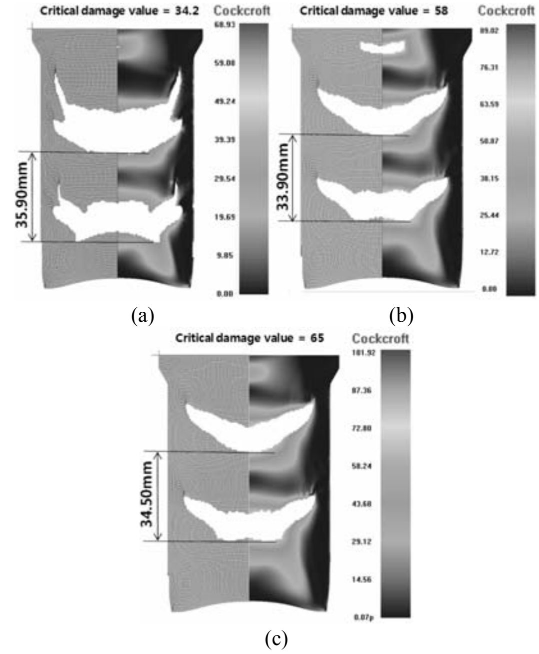

Fig. 8. Simulation results without allowing separation of the specimen from the punch: (a) the instability condition, (b) the tensile fracture condition and (c) the higher critical damage value condition. The dimension of the critical damage value is in MPa.

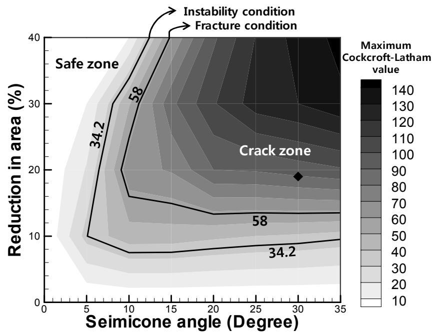

Fig. 9. Processing map of the commercially available steel alloy in the cold extrusion based on the maximum value of the Cockcroft-Latham criterion.

the specimen. This value was applied for the following investigation.

By applying the element deletion method, crack configuration including its shape and the gap distance between cracks were investigated in detail to rediscover the experimental observation available in the work by Saanouni et al. [10]. In the simulation, the same material used in this work was used as before. Initial radius, semicone angle and reduction in area were 35 mm, 30° and 19%, respectively. The length of the specimen used was 75 mm. A shear friction factor of 0.1 was applied as before and 8000 elements were used with an axi-symmetric boundary condition. Punch speed of 5 mm/s was applied in extrusion at room temperature.

In this numerical study, two simulations were carried out with or without separation of the specimen from the punch. As shown in Fig. 7(a), there were two-and-a-half chevron cracks in the experimental result. However, only two chevron cracks occurred in the simulation results when the top side of the specimen was allowed to detach from the punch as shown in Fig. 7(b) and 7(c) when the tensile instability and fracture conditions were used to calculate the limiting damage value, respectively. In addition, only one crack appeared for the critical damage value of 65, which was arbitrarily selected as illustrated in Fig. 7(d). This separation from the punch was due to well-known fish tailing effect in the extrusion process according to the continuous characteristics of extrusion.

On the other hand, when the simulation was carried out with no separation boundary condition from the punch as shown in Fig. 8, the chevron cracking was similar to the experimental result as shown in Fig. 8(b) when the critical damage value was 58. It was found in this figure that the level of critical damage factors affects the evolution of chevron cracks. As shown in Fig. 8(a), when the instability condition was used to calculate the critical damage factor of 34.2, the cracking was not estimated well, leading to a larger gap distance between cracks. Only two cracks occurred at the critical damage value of 65 in Fig. 8(c). In addition, the smaller crack near the punch was not formulated yet.

However, when the tensile fracture condition was used for calculation of the critical damage factor of 58 according to the tensile fracture condition with fracture strain of 0.19 as given in reference [10], the smaller crack was predicted well with prediction of a better gap distance between cracks of 33.90 mm as shown in Fig. 8(b) as well. Therefore, it was construed that the experimental data was produced from the case of no separation boundary condition from the punch. Therefore, the introduction of a proper critical damage value and boundary condition for the element deletion scheme is crucial because the shapes, size of the crack and gap distance between cracks are subject to change depending on its value and condition.

4. Processing map in the cold extrusion

In the previous section, the chevron crack was successfully predicted by the developed numerical scheme. Since the critical design and process control issue in the extrusion is to prevent possible chevron cracking during the process, a processing map was calculated based on the Cockcroft-Latham fracture criterion.

It was shown in the earlier work that chevron cracking in the cold extrusion was dependent on the reduction in area, die semicone angle, material property of the specimen and friction condition. The specimen was fixed as commercially available steel alloy with the flow stress of $\bar{\sigma} = 475\bar{\varepsilon}^{0.1}$ MPa from the reference [10]. Initial radius and length of the specimen used in the present investigation were 35 mm and 75 mm, respectively. The shear friction factor was assumed to be 0.1 as before. The punch speed used was 5 mm/s. To determine the critical damage value, the maximum damage value due to Cockcroft-Latham fracture criterion was calculated with various reductions in area (5 ~ 40%) and semicone angles (2.5 ~ 35°). The numerical results are compared to the experimental results of Saanouni et al. [10] and plotted in Fig. 9. In this figure, the point of diamond represented that chevron cracking occurred.

In Fig. 9, the processing map using instability and fracture conditions predicted occurrence of chevron crack in the experiment properly. In addition, the safe zone was observed mainly for lower reduction in area or relatively small semicone angle as reported in the work by Zimerman et al. [7]. However, the safe zone in the processing map was bigger when the critical damage value was increased. Thus, based on the comparison of chevron cracks between the experimental and simulation results discussed in the previous chapter, tensile fracture condition might predict less conservative safe zone compared to the instability condition. To further validate the region of safety, more experimental data are required. However, the suggested processing map might be beneficial in estimating the chevron cracking for commercially available steel alloy in the cold extrusion without carrying out the real experimentation for practical use.

5. Conclusions

The formation and evolution of chevron cracks were successfully simulated by introducing the element deletion method incorporated with the Cockcroft-Latham fracture criterion in the present study. The Cockcroft-Latham criterion induced chevron cracking, while specific plastic work represented external crack in the cold extrusion. In the simulation with the element deletion method, the number of cracks and ratio of cracking area to the whole area of the specimen were dependent on the element size and boundary condition at the punch interface. These values were found to be converged for the specific or smaller element size. The simulation results were reasonable compared to the experimental observations available in the literature when proper simulation conditions such as no separation boundary condition and tensile fracture condition for determination of initial possible cracking were used. Finally, the processing map for cold extrusion of commercially available steel alloy was developed to prevent chevron cracks for practical use.

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References

[1] A. M. Freudenthal, *The inelastic behavior in solids*, 1st ed., Wiley, New York (1950).

[2] M. G. Cockcroft and D. J. Latham, Ductility and workability of metals, *J. Inst. Met.,* 96 (1968) 33-39.

[3] S. E. Clift, P. Hartley, C. E. N. Sturgess and G. W. Rowe, Fracture prediction in plastic deformation processes, *Int. J. Mech. Sci.,* 32 (1990) 1-17.

[4] A. S. Wifi, A. N. Abdel-Hamid and E. Abbasi, Computer-aided evaluation of workability in bulk forming processes, *J. Mater. Process. Technol.,* 77 (1998) 285-293.

[5] H. S. Kim, Y. T. Im and M. Geiger, Prediction of ductile fracture in cold forging of aluminum alloy, *J. Manuf. Sci. Eng. Trans. ASME,* 121 (1999) 336-344.

[6] B. Avitzur, Analysis of central bursting defects in extrusion and wire drawing, *J. Eng. Ind. Trans. ASME,* 90 (1968) 79-91.

[7] Z. Zimerman, H. Darlington and E. H. Kottcamp Jr., Selection of operating parameters to prevent central bursting defects during cold extrusion, *Wire J. Int.,* 16 (1983) 64-68.

[8] Z. Zimerman and B. Avitzur, Analysis of the effect of strain

hardening on central bursting defects in drawing and extrusion, *J. Eng. Ind. Trans. ASME,* 92 (1970) 135-145.

[9] N. Aravas, The analysis of void growth that leads to central bursts during extrusion, *J. Mech. Phys. Solids,* 34 (1986) 55-79.

[10] K. Saanouni, J. F. Mariage, A. Cherouat and P. Lestriez, Numerical prediction of discontinuous central bursting in axi-symmetric forward extrusion by continuum damage mechanics, *Comput. Struct.,* 82 (2004) 2309-2332.

[11] C. McVeigh and W. K. Liu, Prediction of central bursting during axi-symmetric cold extrusion of a metal alloy containing particles, *Int. J. Solids Struct.,* 43 (2004) 3087-3105.

[12] J. O. Hallquist, *LS-DYNA theory manual.* Livermore Software Technology Corporation, USA (1998).

[13] *ANSYS Advanced Analysis Techniques Guide*, ANSYS Release 10.0, ANSYS Inc. Canonsburg, USA (2005).

[14] H. S. Alsos, A comparative study on shell element deletion and element splitting, Impact & Crashworthiness Laboratory, *Report No. 127*, MIT (2004) 1-94.

[15] E. Ceretti, P. Fallbömer, W. T. Wu and T. Altan, Application of 2D FEM to chip formation in orthogonal cutting, *J. Mater. Process. Technol.,* 59 (1996) 169-180.

[16] H. C. Lee, J. S. Choi, K. H. Jung and Y. T. Im, Application of element deletion method for numerical analyses of cracking, *J. Achievements Mater. Manuf. Eng.* 35 (2009) 154-161.

[17] S. Y. Kim and Y. T. Im, Three-dimensional finite element analysis of non-isothermal shape rolling, *J. Mater. Process. Technol.,* 127 (2002) 57-63.

[18] D. Y. Kwak, J. S. Cheon and Y. T. Im, Remeshing for metal forming simulations part I: Two-dimensional quadrilateral remeshing, *Int. J. Numer. Methods Eng.,* 53 (2002) 2463-2500.

[19] K. Komori, Simulation of chevron crack formation and evolution in drawing, *Int. J. Mech. Sci.,* 41 (1999) 1499-1513.

[20] T. Altan, S. I. Oh and H. L. Gegel, *Metal forming: fundamentals and applications*, American Society for Metals, Metals Park, OH, (1983).

[21] V. Nagpal, T. Altan and R. Gagne, Computer-aided design and manufacturing of dies for lubricated extrusion of shapes, *J. Mech. Work. Tech.,* 1 (1977) 183-201.

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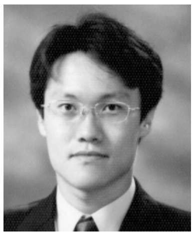

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