Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 35
ISSUE 2
August
2009

Application of element deletion method for numerical analyses of cracking

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Received 19.01.2009; published in revised form 01.08.2009

Analysis and modelling

ABSTRACT

Purpose: To develop a numerical algorithm to simulate cracking and its evolution for machining, shearing and multi-pass hot bar rolling processes.
Design/methodology/approach: Element deletion method was adopted for developing a numerical algorithm and implemented to a rigid-viscoplastic finite element program. Cockcroft-Latham and specific plastic work criteria were incorporated in the present investigation for simulating cracking and shearing processes. An instability condition for the tension was assumed to be valid to determine a critical damage factor for initiation of possible cracking.
Findings: The developed element deletion algorithm was simple to be applied for simulating cracking and shearing patterns for the processes applied. Cockcroft-Latham and specific plastic work fracture criteria were reasonable in predicting the internal and external crack, respectively.
Research limitations/implications: The research finding can be utilized for investigating occurrence of external and internal cracking involved with metal forming processes such as Chevron cracking in extrusion.
Practical implications: By expanding the current approach to determine a processing map for extrusion the processing condition to prevent Chevron cracking can be determined easily and utilized in industry. Also, the current investigation can be easily expanded to other process design and control.
Originality/value: Numerical algorithm based on the element deletion method was developed and implemented to the existing finite element program to examine the processes including cracking phenomenon. The applicability to utilize a critical damage factor for the fracture criteria based on the instability was evaluated.
Keywords: Cracking; Element deletion method; Specific plastic work; Instability; Finite element technique

Reference to this paper should be given in the following way:
H.C. Lee, J.S. Choi, K.H. Jung, Y.T. Im, Application of element deletion method for numerical analyses of cracking, Journal of Achievements in Materials and Manufacturing Engineering 35/2 (2009) 154-161.

1. Introduction

Metal forming processes are very efficient in manufacturing several products at various processing conditions. However, depending on material condition and process variables the products can develop several types of defects such as internal and external cracking, affecting their strength and product quality significantly. Minute external or internal cracks can propagate and eventually lead to total failure of the part. As a result, the fatigue strength is deteriorated drastically. Therefore, formation of internal and external cracking should be prevented at the design stage of the process. In order to fully control such defect formation understanding and prediction of possible cracking and its evolution are necessary.

For investigation of the internal or external cracking, study on fracture criteria is essential. Generally, fracture can be classified as brittle, ductile and fatigue fracture. Brittle fracture occurs when the principal tensile stress exceeds the yield stress or fracture strength. Ductile fracture also occurs by tensile stress or maximum shear stress in a uni-axial stress state. However, it is difficult to predict ductile fracture in a multi-axial stress state and fracture criteria also vary depending on the process conditions and material. Hence, many research works on ductile fracture have been performed so far.

Early investigations for the fracture analysis were concentrated on determination of fracture criteria and prediction of the position of fracture based on energy criteria. Freudenthal [1] used an effective stress for stress component and Cockcroft and Latham [2] employed maximum principal stress to calculate the energy term. Brozzo et al. [3] suggested the ratio between the maximum principal stress and maximum principal stress minus mean normal stress and Oyane [4] introduced the ratio between mean normal and effective stress. These criteria were applied and compared for various processes by Clift et al. [5], Wifi et al. [6] and Kim et al. [7]. According to these works, prediction of cracking positions for the investigated processes was reasonable due to specific plastic work and Cockcroft and Latham criteria but no general rules are available for general applications.

Even though the position of fracture could be reasonably determined for certain processes, it is difficult to predict evolution of cracking to identify detail shape of cracking. Thus, finite element (FE) technique with fracture modeling has been applied recently for the analysis because of solution accuracy and generality for the applications. Moritoki and Okuyama [8] suggested to introduce a ratio between effective and limit strain due to instability in their work to determine workability for cold extrusion. Also [9] investigated the effect of element deletion and separation method for mode I tearing and plate cutting in terms of energy dissipation and load aspects. Ceretti et al. [10] applied FE simulation using element deletion method for orthogonal machining process. Komori [11] applied element separation method to blanking using the commercial FE program. Saanouni et al. [12] applied continuum damage mechanics to thermo-elastoplastic based FE program and predicted the crack formation in cold extrusion. McVeigh and Liu [13] used micro mechanical cell modelling technique and predicted the occurrence and position of chevron cracks in extrusion and edge cracks in rolling. Özel [14] investigated the frictional effect for the orthogonal cutting by using conventional FE program with very fine mesh and remeshing method only. Woon et al. [15] investigated the effect of tool edge radius on chip thickness in the micromachining process using the Lagrangian-Eulerian method.

In the present study, cracking analysis algorithm was developed by applying the element deletion method and linked to in-house rigid-thermo-viscoplastic FE program CAMP*form* [16, 17]. Developed algorithm was incorporated with specific plastic work and Cockcroft and Latham fracture criteria to simulate orthogonal machining, shearing and multi-pass hot bar rolling processes. In order to determine the critical value where cracking initiates instability condition was used and the effect of number of elements on chip formation examined for the machining process.

2. Finite element fracture analysis based on the element deletion method

2.1. Finite element formulation

The rigid-thermo-viscoplastic FE approach proposed by Lee and Kobayashi [18] has been used for deformation analyses. The approach was essentially a coupled procedure to solve equilibrium and energy equations in a staggered manner, in which a rigid-thermo-viscoplastic constitutive model with von Mises yield criterion was used by neglecting the body and inertia forces.

Equilibrium equation: $\sigma_{ij,j} = 0$ in V (1)

Energy equation: $kT_{,ii} - \tilde{\rho} C_p \dot{T} + \dot{r} = 0$ (2)

Constitutive equation: $\sigma'_{ij} = 2\mu\dot{\varepsilon}_{ij},\ \mu = \dfrac{\bar{\sigma}}{3\dot{\bar{\varepsilon}}}$ (3)

Yield criterion:

$$\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T) = \sqrt{\frac{3}{2}\sigma'_{ij}\sigma'_{ij}}\ ,\ \dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad (4)$$

Compatibility equation: $\dot{\varepsilon}_{ij} = \dfrac{1}{2}(v_{i,j} + v_{j,i})$ (5)

Incompressibility: $\dot{\varepsilon}_{kk} = 0$ (6)

Boundary conditions:

$$v_i = v_i^* \text{ on } S_U \quad (7)$$

$$\sigma_{ij} n_j = t_i^* \text{ on } S_F \quad (8)$$

$$T = T^* \text{ on } S_T \quad (9)$$

$$q_n = q_n^* = -k\frac{\partial T}{\partial n} \text{ on } S_Q \quad (10)$$

Here, σ_{ij}, σ'_{ij}, and $\bar{\sigma}$ represent the stress tensor, deviatoric stress tensor and effective stress in that order. $\dot{\varepsilon}_{ij}$, $\dot{\bar{\varepsilon}}$, and $\bar{\varepsilon}$ are the rate of deformation tensor, effective strain rate and effective strain in that order as well. S_U and S_F represent the regions where velocity and traction boundary conditions are prescribed, respectively. As part of the traction boundary conditions, the interfacial friction condition was applied on the boundary, S_C. T, k, $\tilde{\rho}$, C_p in Equation 2 are the temperature, conductivity, density, and specific heat of the material in that order. $\dot{r}$ is the heat generation rate due to deformation of the billet and frictional heat generation between the billet and dies. The temperature and heat flux boundary conditions were prescribed on S_T and S_Q, respectively. q_n represents the heat flux between the billet and dies and n indicates the outward normal direction at the interfacial surface. The thermal properties are dependent on the temperature in the simulation program.

The constant shear friction model described in Equation 11 was used to apply the frictional force at the interface between the billet and dies:

$$t_i^* = -m_f k_s \frac{2}{\pi} \frac{(\mathbf{v}_r)_i}{\|\mathbf{v}_\mathbf{r}\|} \tan^{-1}\left(\frac{\|\mathbf{v}_\mathbf{r}\|}{\psi}\right) \text{ on } S_C \tag{11}$$

where m_f and k_s represent the shear friction factor and shear yield strength of the material, respectively and v_r is the relative velocity between the billet and dies. In the present study, $\psi = 0.05$ was used for simulations.

2.2. Numerical algorithm based on the element deletion method

In the element deletion method, element volume will be removed when the necessary condition for element deletion is met during the deformation. Thus, it might induce physical inaccuracy compared with the element splitting method. However, the element deletion method can overcome the stress concentration at the cracked surface by deleting cracked elements during simulations. So it can prevent over-estimation of stress and strain values [9]. In addition, if the element size used in simulations becomes smaller, solution accuracy can be improved. Since the numerical algorithm was simple to apply, it was selected for the fracture analysis in the present study.

In order to develop a numerical algorithm using the element deletion method, three major elements are necessary. At first, valid fracture criteria are needed for determining those elements deleted. In this study two fracture criteria based on generalized plastic work per unit volume and Cockcroft-Latham were selected as follows:

$$\int_0^{\bar{\varepsilon}_f} \bar{\sigma}\, d\bar{\varepsilon} = C_1 \tag{12}$$

$$\int_0^{\bar{\varepsilon}_f} \sigma_{P,MAX}\, d\bar{\varepsilon} = C_2 \tag{13}$$

Here, $\sigma_{P,MAX}$ is the largest tensile principal stress and $\bar{\varepsilon}_f$ represents the effective strain at the initial cracking. C_1 and C_2 represent the critical damage factors depending on the material and criterion. In the present analysis, these values were determined by the instability condition in which $\bar{\varepsilon}_f$ = n where n is a strain hardening parameter of the material.

At second, implementation of element deletion and preparation for disconnected node removal are necessary. During the element deletion stage, some nodes might be isolated and disconnected from the neighbouring elements as shown in Fig. 1 because of element deletion. In this case, the disconnected or isolated node should be removed for the continuing FE simulations.

At third, rearrangement of the boundary conditions after the element deletion. Since some elements might be deleted depending on the level of critical damage factor of each fracture criterion, the new boundary surface would be generated. Thus, the boundary conditions should be reconstructed accordingly. Otherwise the continuing FE forming simulation would not be working.

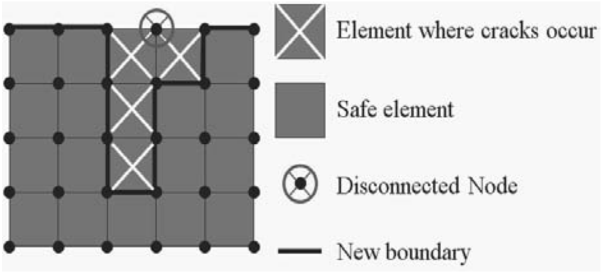

Fig. 1. Schematic diagram of the element deletion method

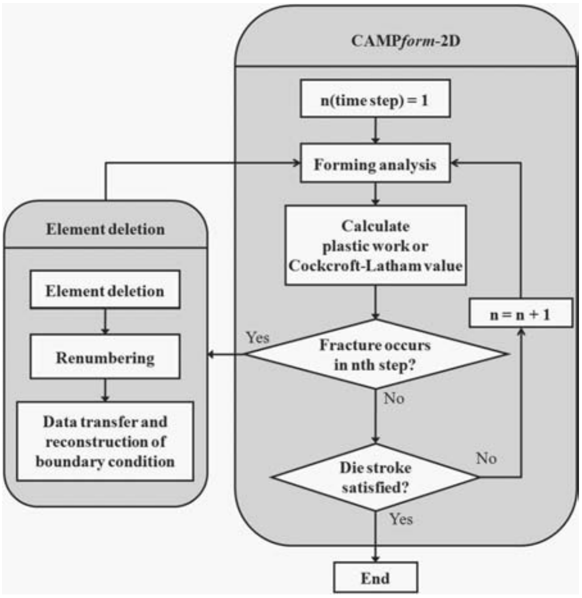

Fig. 2. Flow chart of the cracking analysis based on the element deletion method

The numerical sequence for applying the element deletion method to the FE simulator is illustrated in Fig. 2. In this figure, CAMP*form*-2D was chosen for the FE simulator. However, any simulators can be used for applying the current deletion algorithm developed.

According to this figure, damage factors depending on the fracture criteria are calculated for every *n*th time step of deformation during rigid-viscoplastic FE simulations. Comparison of the elemental value of damage factor with the critical value depending on fracture criterion introduced earlier will determine which elements should be deleted at the current deformation step. If element deletion does not occur, forming simulation for the next time step will continue. When the element deletion occurs, information of the current mesh system including the candidate element data for deletion will be transferred to the element deletion routine.

At the element deletion routine, candidate element will be deleted and element renumbering for reducing computation time required. Depending on the new mesh layout with new boundary conditions, the continuing forming simulation for the next time step will be carried out until the end of simulations.

3. Applications

The developed numerical algorithm was applied to simulate the orthogonal machining, shearing and multi-pass hot bar rolling processes.

3.1. Orthogonal machining

In Fig. 3, the schematic and process condition of the orthogonal machining process are given [19]. The shear friction factor in Equationn 11 was assumed to be 0.1 in the present investigation.

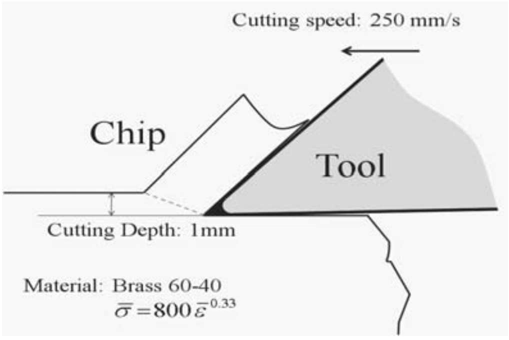

Fig. 3. Schematic diagram of orthogonal machining

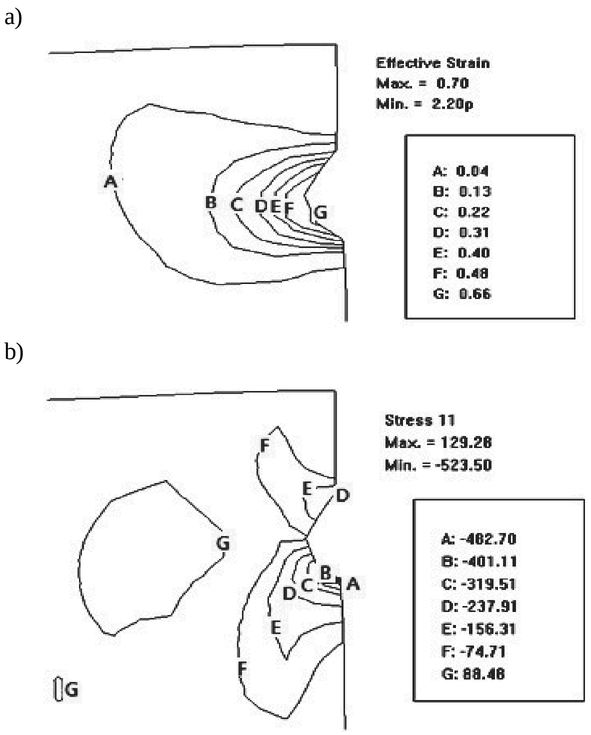

Fig. 4. Distributions of (a) the effective strain and (b) maximum principal stress

In Fig. 4, the distributions of effective strain and maximum principal stress are given. According to this figure, the maximum locations are different depending on the fracture criteria, resulting in different element deletions as shown in Fig. 5.

Fig. 5 shows the comparison of the element deletions at the same time step depending on Cockcroft-Latham and specific plastic work fracture criteria. In this figure it is clear that the internal crack in front of the edge of the machining tool was formed at an early stage of the process due to Cockcroft-Latham fracture criterion. However, this does not occur for the simulation case with the specific plastic work criterion. Thus, it is obvious that evolution of the cracking phenomenon is dependent on the fracture criterion. Since the cracking mode is more reasonable for the specific plastic work approach, this will be applied for the continuing calculations.

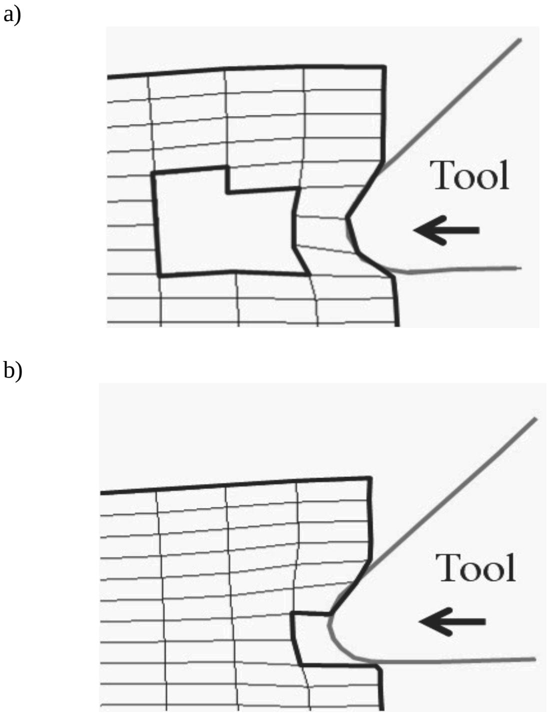

Fig. 5. Crack initiation at the same time step depending on different fracture criteria: (a) Cockcroft-Latham and (b) specific plastic work

Fig. 6 shows the chip formation calculated by FE simulations at various steps. In this Figure, the surface cracking in the chip was clearly described in the numerical simulations based on the specific plastic work criterion.

The cracking in the chip was observed similar to the experimental observation in the literature [19] as shown in Fig. 7. By comparing the FE and experimental results, the chip formation was reasonable.

The effect of the number of elements used in simulations on shearing patterns is compared in Fig. 8. In this Figure, as the number of elements increases the cracking and shearing patterns of the chip and machined surface vary. According to this investigation, the machining process can be effectively simulated by applying the developed algorithm.

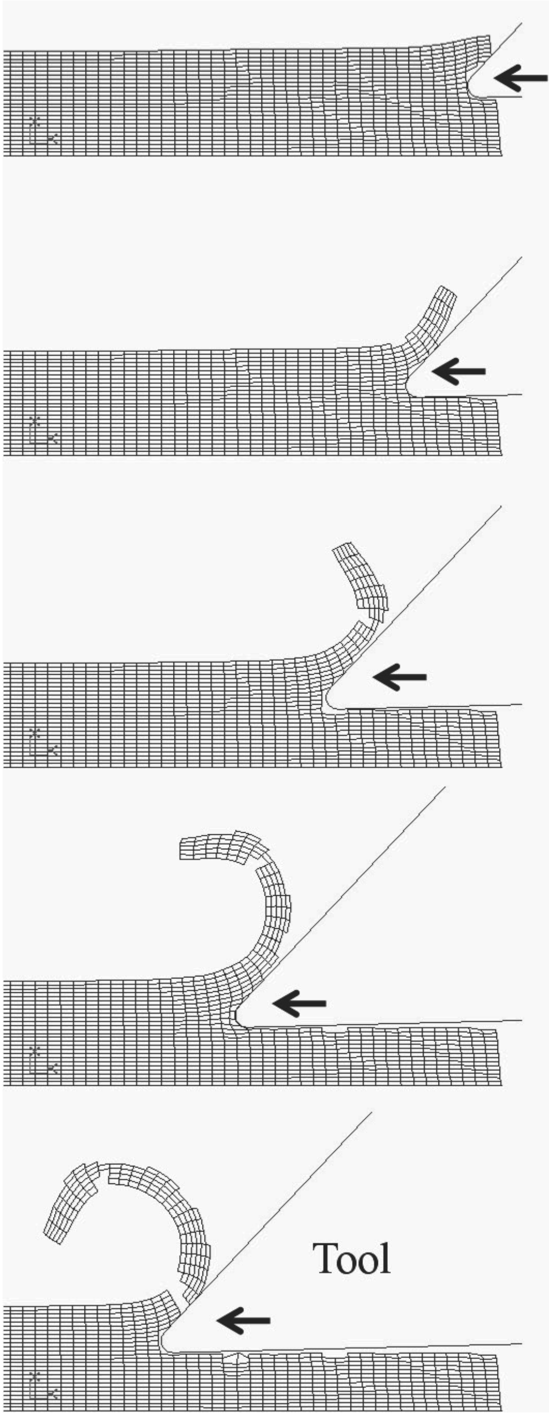

Fig. 6. Comparison of chip formation due to the specific plastic work

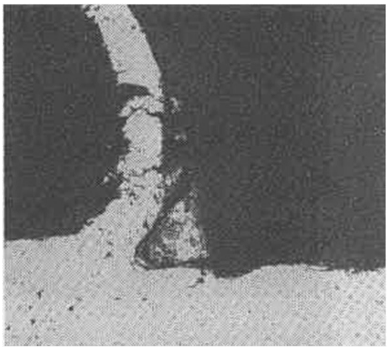

Fig. 7. Experimental observation of chip formation in reference [19]

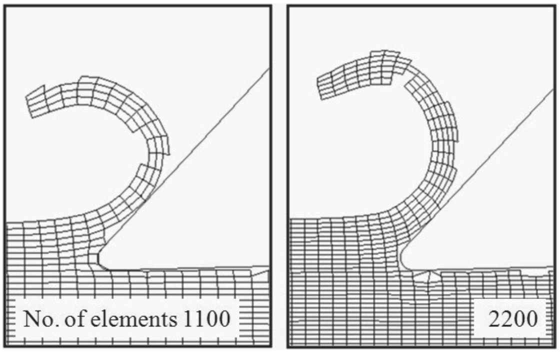

Fig. 8. Effect of the number of elements on chip formation

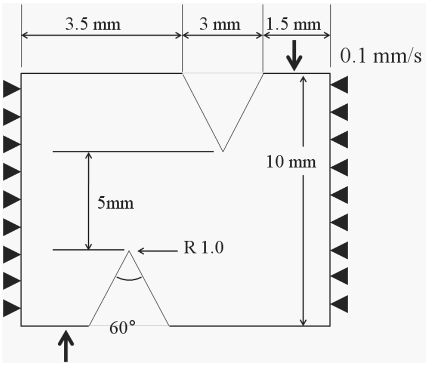

Fig. 9. Shearing of the notched specimen [20]

3.2. Shearing of the notched specimen

The second example is shearing of the notched specimen as shown in 0. In this figure, the material was Al 7108 whose material property can be interpolated as $\sigma = 497\ \varepsilon^{0.03}$ MPa. Shear friction factor was assumed to be 0.1 as before. The speed of shearing dies was 0.01 mm/s and the number of elements used was 5000. Fixed boundary condition was applied at both ends as shown in this Figure. Two fracture criteria of Cockcroft-Latham and specific plastic work were also used in the present simulations.

The distributions of the effective strain and maximum principal stress are given in Fig. 10. Depending on these distributions, the element deletions were obtained at the initial stage as shown in Fig. 11.

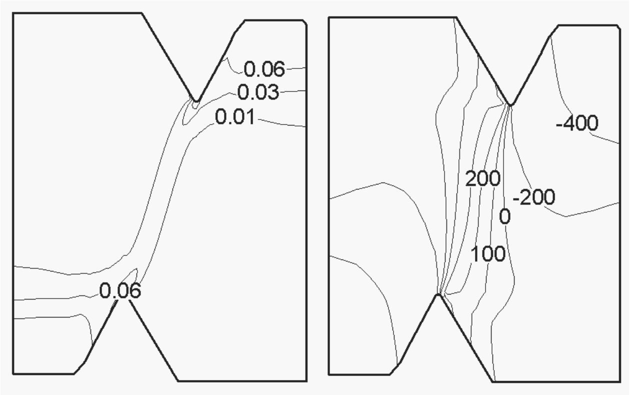

Fig. 10. Distributions of (a) the effective strain and (b) maximum principal stress in MPa

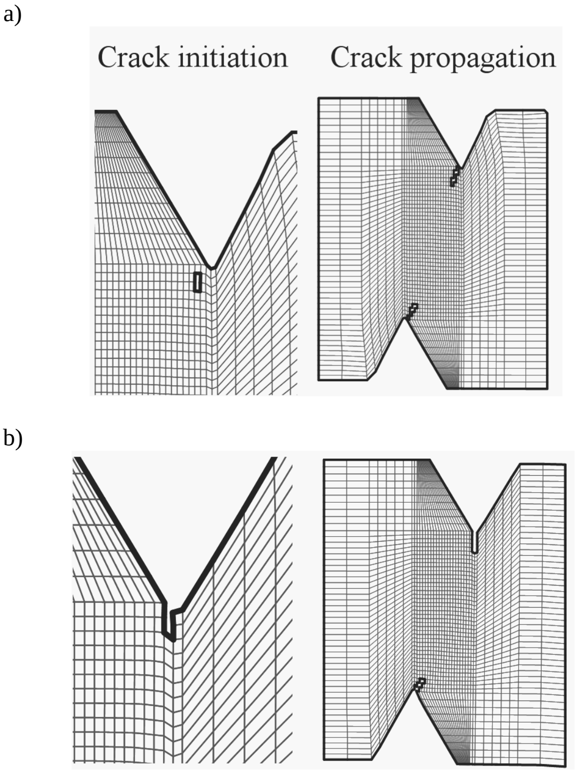

Fig. 11. Initial stage of crack initiation and propagation depending on the fracture criteria: (a) Cockcroft-Latham and (b) specific plastic work fracture criteria

Fig. 11 shows the initiation and propagation of the crack for the shearing of the notched specimen. According to this figure the initial cracking occurs at the internal and external location due to Cockcroft-Latham and specific plastic work criterion, respectively, similar to the machining case. Also, the mode of propagation of the cracking is clearly different depending on the fracture criterion. In this case it was found that the Cockcroft-Latham criterion is more reasonable.

The intermediate stage of deformation is given in Fig. 12. According to this figure the specific plastic work criterion gives two different cracking tips which have different direction of crack propagation. Because of the different crack propagation, final shape of the cracking based on the specific plastic work approach was curved compared to the Cockcroft Latham criteria.

In Fig. 13, the final stage of cracking and the experimental observation available in reference [20] are given. In this figure a reasonable agreement between the numerical prediction with the Cockcroft-Latham criteria and experimental data is observed. Thus, Cockcroft-Latham criterion gives better solution for this process.

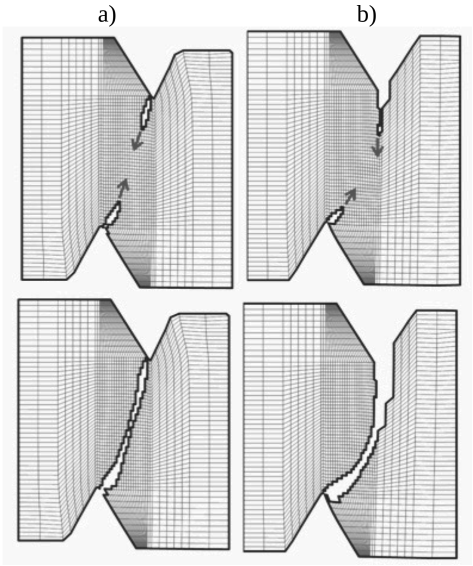

Fig. 12. Intermediate stage of crack propagation depending on the fracture criteria: (a) Cockcroft-Latham and (b) specific plastic work

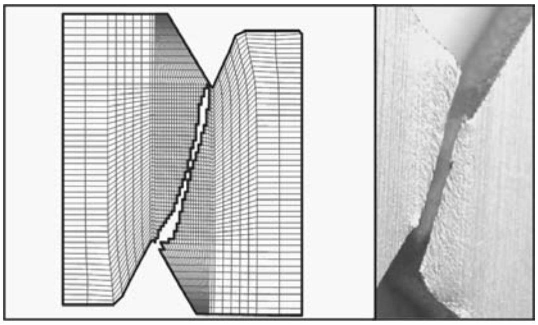

Fig. 13. Evolution of cracking based on the Cockcroft-Latham criterion and experimental observation in reference [20]

3.3. Multi-pass hot bar rolling

In order to examine the wrinkle type surface crack on the steel wire as shown in Fig. 14, specific plastic work approach [21] was introduced as a fracture criterion by solving a three dimensional multi-pass hot bar rolling problem. Initial temperature of the billet was 1080ºC and the width, height and length of the billet were 80 mm, 80mm and 250 mm, respectively. Roll temperature was assumed to be constant at 20ºC and its rotational speed was 10 rpm. The material was low carbon steel. The shear friction factor of 0.6 was determined by comparing the geometrical deformation between experiment and simulation. Total number of elements for the billet used was 4598 as shown in Fig. 15. Detail conditions for the thermal analysis are given in the reference [21].

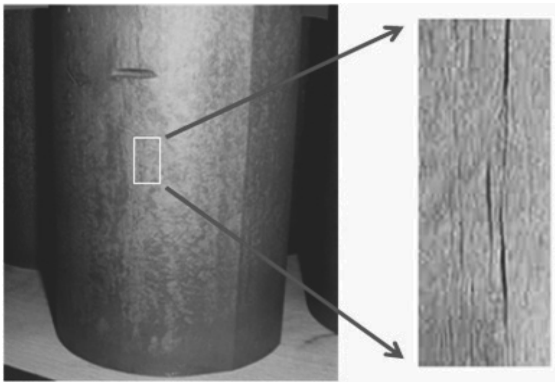

Fig. 14. Surface cracks on steel wire of low carbon steel

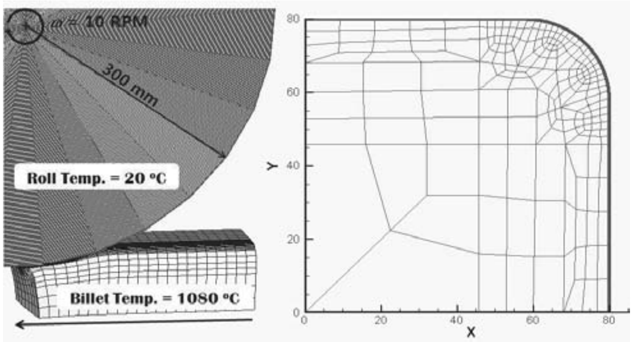

Fig. 15. Schematic diagram of multi-pass hot bar rolling

Simulation results obtained by adopting the developed algorithm are described in Fig. 16. In this Figure, the element deletion method based on the specific plastic work represents the crack initiation well. In addition, the change of the shape of crack can be examined after crack initiation through the numerical analysis for the multi-pass hot bar rolling as shown in the same Figure. By comparing with the earlier work by Kwon et al. [22], the location of the surface crack observed in industry was similar to the present one in this Figure.

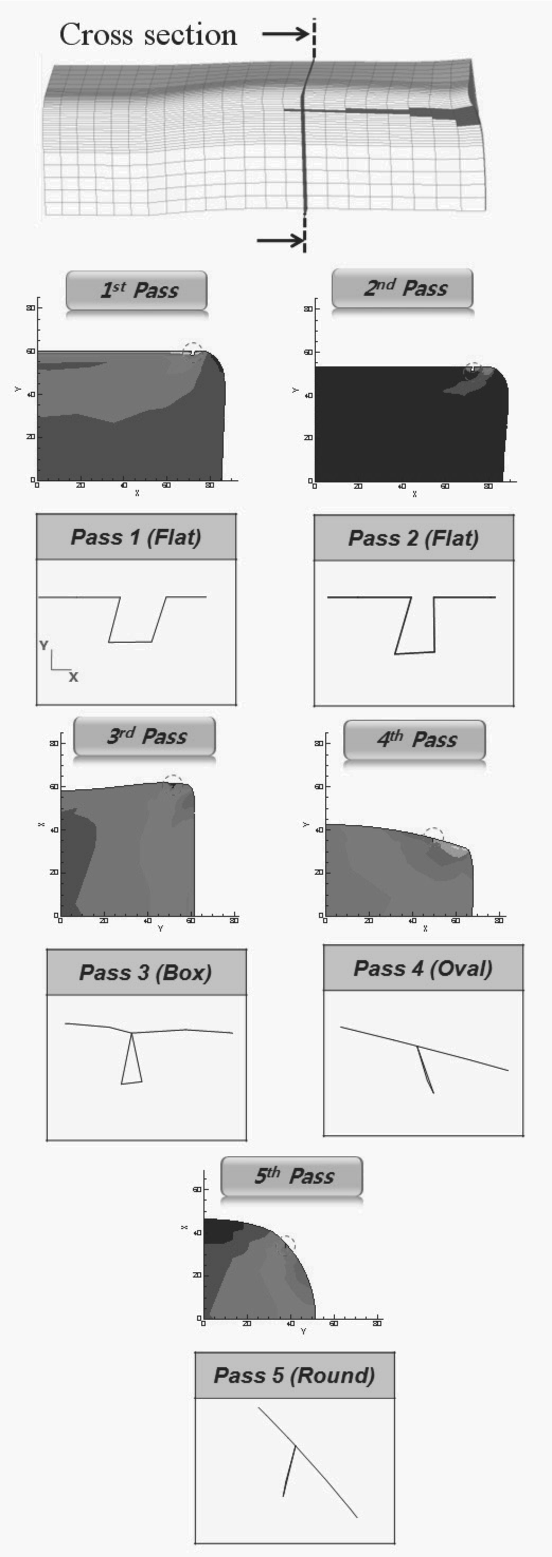

Fig. 16. Crack initiation and its evolution in the multi-pass rolling for steel wire of low carbon steel

4. Conclusions

The machining, shearing and multi-pass hot bar rolling processes were successfully simulated by introducing the element deletion method incorporated with specific plastic work and Cockcroft-Latham fracture criteria in the present investigation. Instability condition was applied to determine the critical damage factors for both fracture criteria. The simulation results were reasonable compared with the experimental observations available in references. However, Cockcroft-Latham and specific plastic work fracture criterion predicted the internal and external crack, respectively, according to the present investigation. In order to examine the crack occurrence and evolution based on the element deletion method, sufficiently small size of elements was needed. The numerical algorithm developed can easily be applied for other processes such as extrusion and drawing. Thus, it can be utilized to predict a possible cracking at the process design stage.

Acknowledgements

This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the National Research Laboratory and Research Grant from POSCO. Program funded by the Ministry of Education, Science and Technology (No. R0A-2006-000-10240-0). Both research grants were very much appreciated.

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