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Characterization of dynamic hardening behavior using acceleration information

J.-H. Kim[a]*, J.-S. Park[a], F. Barlat[a], F. Pierron[b]

[a]*GIFT, Pohang University of Science and Technology, San 31 Hyoja-dong, Nam-gu, Pohang, Gyeongbuk 790-784, Republic of Korea*
[b]*Faculty of Engineering and the Environment, University of Southampton, Highfield, Southampton, SO17 1BJ, UK*

Abstract

Crash analysis simulation is very important in automotive industry to assess automotive crashworthiness and safety. In the FE simulation, accurate dynamic hardening behavior should be used as input data to provide reliable results. But, it is difficult to obtain precise hardening properties at intermediate or high strain rates due to inaccurate measurement of load caused by the inertial effect. In this study, a new methodology was applied to retrieve dynamic strain hardening properties of sheet metal specimens. The virtual fields method (VFM) was adopted as an inverse method to identify hardening parameters without load information. As an initial study, Swift model for a rate independent hardening law was selected for an elasto-plastic constitutive model. In order to validate the proposed methodology in the experiments, a new type of high speed tensile tester for sheet metal specimens was built and high speed tensile tests were performed. Digital image correlation technique using a high-speed camera was utilized to measure strain and acceleration fields so that the identification is carried out from the measured quantities. The validation of the proposed VFM identification procedure using the acceleration will be performed by comparing with the conventional procedure using a load-cell.

Keywords: dynamic hardening behavior; plasticity; sheet metal; virtual fields method; full-field measurements;

* Corresponding author. Tel.: +82-54-279-9058; fax: +82-54-279-9299.
E-mail address: jinkim@postech.ac.kr

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1. Introduction

Crash analysis using finite element (FE) simulation is now essential in auto companies to evaluate automobile crashworthiness. In order to acquire reliable simulation results, precise material behaviors at intermediate or high strain rates should be fed as input. However, the dynamic hardening behavior of materials at high strain rates is not easily characterized because accurate measurement of load is difficult due to the inertial effect [1]. The aim of the present study is to characterize the dynamic strain hardening behavior of thin steel sheet specimens using the virtual fields method (VFM) [2]. The identification is carried out using the acceleration fields without utilizing load information. To determine the hardening parameters at high strain rates, high speed tensile tests are conducted on advanced high strength steel (AHSS) sheet specimens and full-field displacement fields are measured by a digital image correlation (DIC) technique using a high-speed camera. Then, a proper elasto-plastic constitutive model is chosen and the VFM is used as an inverse analytical tool to determine the constitutive parameters. In this study, the methodology is introduced and a wider validation of the proposed identification procedure against simulated and experimental data is presented.

2. Identification procedure

2.1. Logarithmic (true) strain

In order to simulate the measurement points from DIC, fine mesh size was employed first. Three nodes triangular shell elements were used. Reference (undeformed) and deformed coordinates of measurement points were recorded and the whole area of interest (AOI) was meshed using triangular elements.

The deformation gradient F for each triangle was calculated from the undeformed and deformed coordinates of measurement points using the analytical approach adopted in [3] and the theory of finite deformation [4]. A plane stress state and incompressibility (det(F)=1) in plasticity were assumed. Then the logarithmic strain tensor $\varepsilon_{\ln}$ was obtained from the deformation gradient F through the left stretch tensor V ($V^2=F^TF$) as in equation (1).

$$\varepsilon_{\ln} = \sum_{i=1}^{3} \ln(\lambda_i) r_i \otimes r_i \tag{1}$$

where λ_i and r_i are the eigenvalues and eigenvectors of the left stretch tensor V respectively.

2.2. Constitutive model

Choosing a constitutive model which can describe the dynamic strain hardening behavior properly is important. In this study, von Mises yield criterion for isotropic material and Swift model for a rate independent hardening law were chosen as an initial study. The associated flow rule was assumed.

$$\text{Swift model: } \sigma_s = K(\varepsilon_o + \varepsilon_p)^n \tag{2}$$

where σ_s is the current yield stress and ε_p the equivalent plastic strain. K, ε_0 and n are the material parameters to be identified.

2.3. The virtual fields method

In this study, the virtual fields method (VFM) was used for an inverse method to retrieve the constitutive parameters from the measured deformation fields. The VFM makes use of the principle of virtual work which describes the condition of global equilibrium. The equilibrium equation in the case of elasto-plasticity for dynamic loading, and in absence of body forces, can be written as follows:

$$-\int_V \left[\int_0^t \dot{\sigma}_{ij} dt \right] \varepsilon_{ij}^* dV + \int_{S_f} T_i u_i^* dS = \int_V \rho a_i u_i^* dV \tag{3}$$

where $\dot{\sigma}$ is the stress rate which is a function of $\dot{\varepsilon}$ (actual strain rate), σ (actual stress) and unknown constitutive parameters, V the measurement volume, T the distribution of applied forces acting on S_f, ε^* the virtual strain field derived from u^* (the virtual displacement field), ρ the density and a the acceleration.

Material parameters can be determined from the acceleration fields by choosing proper virtual fields which can get rid of the external virtual work (EVW) term including the loads. For an elasto-plasticity problem, the identification is carried out using an iterative procedure [5] to minimize the quadratic gap between the internal virtual work (IVW) and the acceleration term (the right hand side of equation (3)). In this study, simple virtual fields were applied to find the material parameters as in equation (4).

$$u_x^* = 0, \quad u_y^* = (y - y_{\min})(y - y_{\max}) \tag{4}$$

where y is the vertical coordinate of the measurement points in the current (deformed) configuration.

2.4. Speed and Acceleration

The speed fields can be obtained from the measured displacement fields using simple finite difference.

$$v_i(t + \frac{\Delta t}{2}) = \frac{u_i(t + \Delta t) - u_i(t)}{\Delta t} \tag{5}$$

where i can be either x or y and t is time.

The acceleration fields can be computed from the displacement fields by double temporal differentiation as in equation (6). Due to the nature of the quantities, the speed is defined at time $t+\Delta t/2$ and the acceleration is at time t.

$$a_i(t) = \frac{u_i(t + \Delta t) + u_i(t - \Delta t) - 2u_i(t)}{\Delta t^2} \tag{6}$$

3. A novel high speed tensile tester

3.1. Impact frame high speed test (IFHS tests)

In order to validate the proposed methodology in the experiments, a novel high speed tensile tester for sheet metal materials based on [6] has been developed, and the experimental set-up is shown in Fig. 1. In the high speed tensile tester, two metallic frame bars are connected to a hydraulic pump through a coupler, which is designed to be broken when it is put under a certain amount of load. When the pump starts to impose tensile load on the coupler, the coupler endures the load until it reaches to critical load value and elastic strain energy is accumulated in the frame bars at the same time. If the load is increased to break the coupler, the energy within the frame bars is released so that the specimen connected to a frame module is pulled in tension and acceleration fields are generated on the specimen.

3.2. Experiments

For the experimental application, Dual Phase (DP) 780 advanced high strength steel (AHSS) material was used. The sheets were 1 mm thickness, and all the specimens were cut in the rolling direction (RD).

In the experiments, high speed tensile tests on sheet metal specimens were conducted and full-field displacement fields were measured by a digital image correlation (DIC) technique using a high-speed camera (Photron FASTCAM SA-X2). In order to check the temporal variation of strain rate and acceleration, the averages of strain rate and acceleration fields in the loading direction are plotted in Fig. 4 (a). It was observed that maximum strain rate up to 300 1/s and maximum acceleration up to 25 km/s^2 were obtained from the newly built IFHS tester.

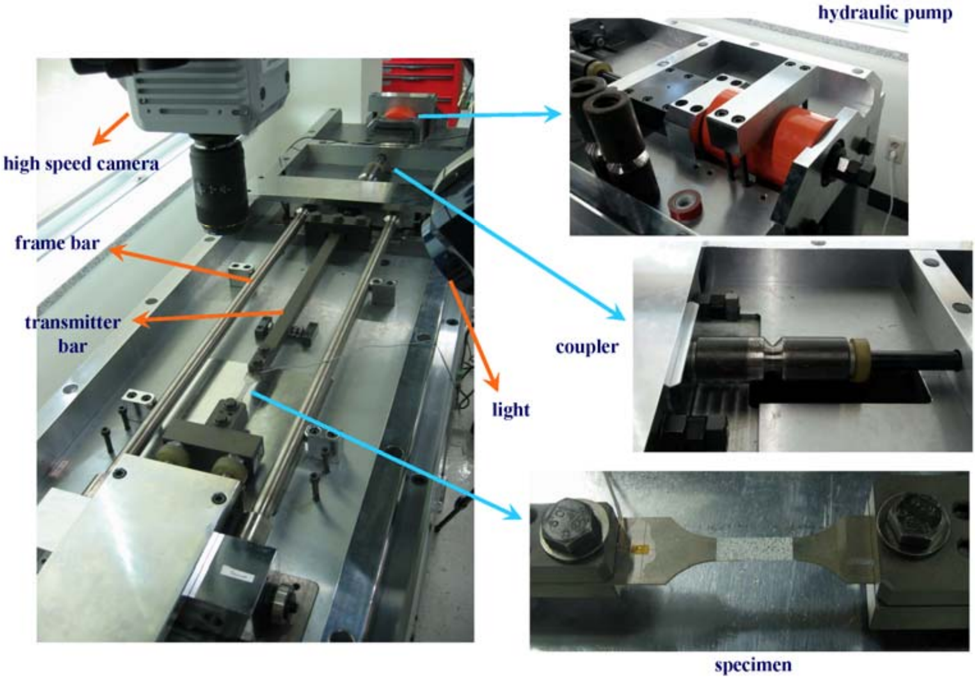


Fig. 1. Impact frame high speed tester.

However, it was observed that the magnitude of acceleration is not high enough to be used for the VFM identification. Therefore, it was considered that it is required to increase the magnitude of acceleration to achieve successful identification with the VFM. It is worth noting here that in the current test set-up, the specimen is pulled from the very beginning due to the grip condition. This pulling condition deteriorates the initial acceleration and thus, the grip condition was modified as shown in Fig. 2. By changing the circular holes to rounded rectangles, the specimen is pulled after certain speed is reached as described in Fig. 3.

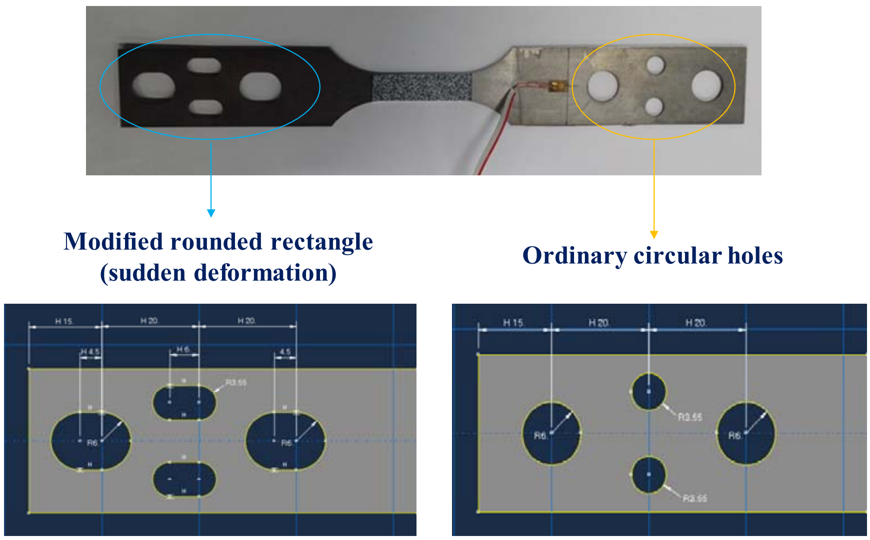


Fig. 2. Modification of grip condition.

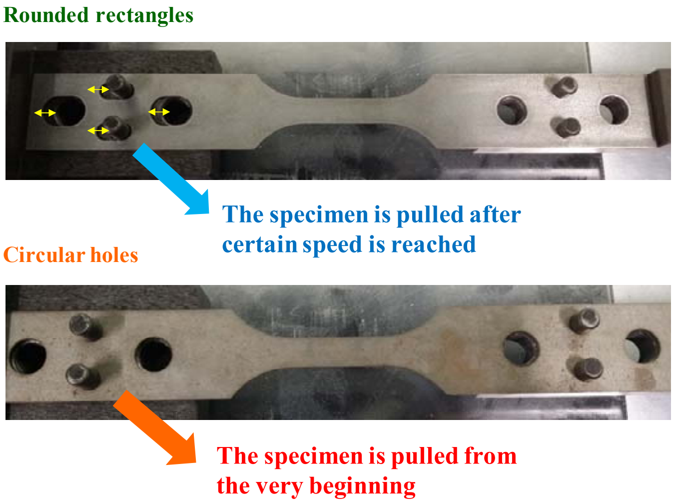


Fig. 3. New grip condition.

The velocity and acceleration (a_Y) in the loading direction and strain rate are compared between the original grip condition and the modified one in Fig. 4.

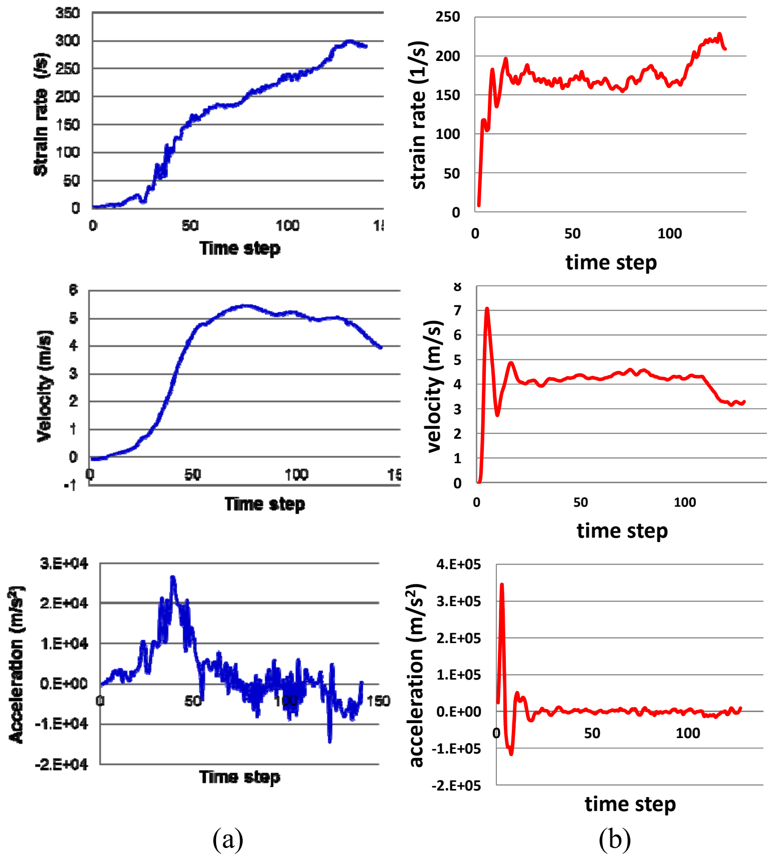
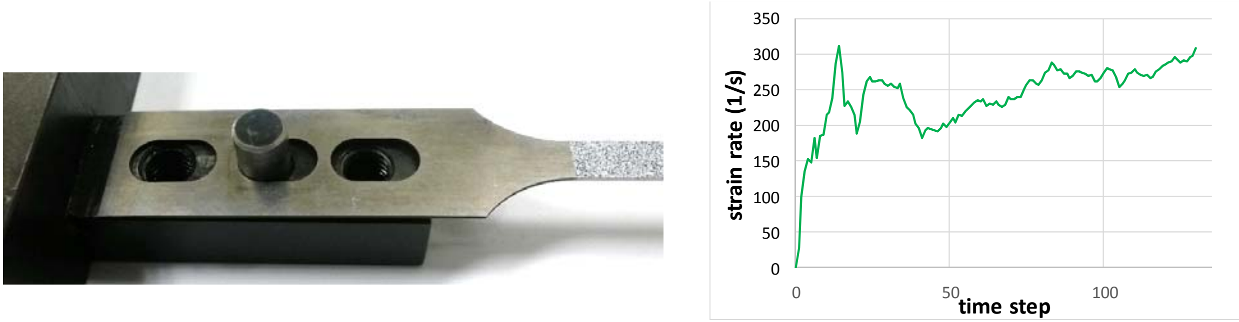


Fig. 4. Comparison of the velocity, acceleration and strain rate between (a) circular holes and (b) rounded rectangles.

Interestingly, the strain rate with the modified grip condition increases suddenly and maintains relatively constant compared to that with the original grip condition as shown in Fig. 4. In addition, the maximum magnitude of acceleration increases dramatically from 2.5×10^4 m/s^2 to 3.5×10^5 m/s^2. Before closing, it is worth mentioning that the acceleration did not increase more though the sliding distance of the specimen was increased from 6 mm to 9 mm (see Fig. 3). Also, another geometry with one rounded rectangle was tried to increase the magnitude of acceleration more as shown in Fig. 5 (a). In this case, the pin diameter was increased from 7 mm to 12 mm, so it was expected that a stronger impact would increase the acceleration magnitude. However, as can be seen in Fig. 5 (b), very strange behavior of strain rate was observed. It was found that the stronger impact on the specimen crushes the end of the rounded rectangle, leading to a sudden drop of the strain rate.



(a) (b)

Fig. 5. (a) Another geometry for grip condition (b) the corresponding strain rate.

Conclusion

In this study, a new methodology has been applied to determine the dynamic true stress-strain curve of sheet metals using the virtual fields method (VFM) without measuring loads. A new high speed tensile tester was built and high speed tensile tests were carried out on sheet metal specimens using a high-speed camera. The validation of the proposed methodology against experimental measurements will be performed. The identification results with the Swift model at various strain rates will be compared with those from the conventional identification procedure using a load-cell.

Acknowledgements

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References

[1] F. Pierron, M.A. Sutton, V. Tiwari, Ultra high speed DIC and virtual fields method analysis of a three point bending impact test on an aluminium bar, Exp. Mech. 51 (2011), 537-563.
[2] F. Pierron, M. Grédiac, The Virtual Fields Method. Springer, 2012.
[3] J. H. Kim, A. Serpantié, F. Barlat, F. Pierron, M. G. Lee, Characterization of the post-necking strain hardening behavior using the virtual fields method, Int. J. Solids. Struct. 50 (2013), 3829-3842.
[4] F. Dunne, P. Nik, Introduction to computational plasticity. Oxford University Press, New York, 2005.
[5] M. Grédiac, F. Pierron, Applying the virtual fields method to the identification of elasto-plastic constitutive parameters, Int. J. Plasticity 22 (2006), 602-627.
[6] D. J. Kim, K. Wille, S. El-Tawil, A. E. Naaman, Testing of cementitious materials under high-strain-rate tensile loading using elastic strain energy, J. Eng. Mech., 137 (2010), 268-275.