Dynamic hardening properties identification utilizing acceleration data by the Virtual Fields Method

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Abstract. Finite element (FE) simulations are very important in the field of automotive, aerospace and defense to evaluate crashworthiness of high strength reinforcing parts. Reliable material properties at high strain rates should be used for the FE simulation to acquire accurate simulation results. However, at high strain rates, it is difficult to obtain accurate stress-strain data because reasonable load data is not easily achieved from the experiments due to ringing problem caused by inertia effect. In this study, the virtual fields method (VFM) which is one of the inverse methods suggests another possibility of identifying hardening properties by utilizing acceleration data from the experiments without using load data. In the current study, a methodology is introduced for this purpose. The minimum magnitude of acceleration necessary to retrieve the hardening properties at high strain rate testing is investigated numerically and experimentally. In addition, a new type of high strain rate testing equipment, impact frame high speed tester (IFHS) is described. Various aspects allowing an increase of the acceleration magnitude in the IFHS are discussed for an optimum application of the methodology. Lastly derived hardening properties with the acceleration by the VFM are discussed.

1. Introduction

Steel is one of the mostly used resources around the globe. Many industries for example, automotive, electronics and defense industries are taking advantage of steel. To guarantee the safety of products, demand on accurate dynamic characteristics of steel became significant.

In evaluating the deformation rate of the steel, strain rate is an important criterion. When the deformation speed changes, flow stress is affected which means that flow stress of the steel depends on the strain rate. Thus, many attempts have been made to understand the high strain rate properties. Charpy [1], Izod [2] test or other types using hydraulic machines are well known methods. However, those methods have several disadvantages like spatial limit and difficulty of obtaining accurate load data. Therefore, it is difficult to identify precise dynamic properties with aforementioned methods.

In order to solve this problem, the virtual fields method (VFM), a material property evaluation method, was used in this study. Especially for high strain rate case, a strong advantage of the VFM is that it does not need load data for evaluation of dynamic properties. When sufficient acceleration data is given, the VFM fully utilizes this data, so that dynamic properties can be identified from only acceleration.
Before real experiments, simulations using ABAQUS were carried out. Many kinds of mechanical tests can be done virtually from FE simulations. In this study, the minimum magnitude of acceleration to identify dynamic property was figured out through FE simulations.

To obtain the sufficient acceleration data from the real experiment, the impact frame high speed tester (IFHS) [3] was used for carrying out dynamic tensile experiments. Attempts to evaluate the dynamic properties of materials using the VFM under high strain conditions using the IFHS have already been made in several previous researches [4, 5]. The IFHS uses the stored elastic strain energy allowing dynamic deformation which is different from conventional ones.

A high speed camera and the digital image correlation technique (DIC) were adopted to capture the deformation and to obtain displacement fields. With a high speed camera, displacement information during whole dynamic deformation was acquired and, acceleration data was captured using the displacements.

An advanced high strength steel (AHSS), DP980 was used for this study.

2. Methodology

2.1. Logarithmic strain

Dense data on the area of interest (AOI) was achieved by using the DIC technique. The whole AOI was covered with triangle mesh. Plane stress state and plastic incompressibility were assumed. As whole deformation process was captured, deformation gradient \( F \) for each triangle element was calculated based on the finite deformation theory [6]. The logarithmic strain tensor \( \varepsilon_L \) was calculated from the deformation gradient \( F \) as in equation (1).

\[
\varepsilon_L = \sum_{i=1}^{3} \ln(\lambda_i) r_i \otimes r_i
\]

where \( \lambda_i \) and \( r_i \) indicates eigenvalues and eigenvectors of the left stretch tensor \( V \) respectively [6].

2.2. Constitutive model

In this study, the Johnson-Cook model with Swift hardening was used to describe the dynamic hardening behavior appropriately.

\[
\sigma = (X_1 (\varepsilon_p + X_2) X_3) \ast (1 + C l n \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})
\]

where \( X_1 \sim X_3 \) are from the Swift hardening law, \( \varepsilon_p \) the equivalent plastic strain, \( \dot{\varepsilon} \) target strain rate, and \( \dot{\varepsilon}_0 \) is the reference strain rate. The Johnson-Cook parameter \( C \) was identified through the VFM which will be introduced below.

2.3. The virtual fields method

In this study, the virtual fields method (VFM) was used to identify constitutive parameters inversely. The principle of virtual work (PVW) makes possible to link extracting the parameters of the constitutive equations from the experimental data such as displacement or strain obtained through the full-field measurement techniques. In case of high strain rate plasticity case, assuming no body force, the PVW can be written as follows:

\[
- \int_V \left[ \int_0^\tau \dot{\varepsilon}_{ij} dt \right] \dot{\varepsilon}_{ij} dV + \int_{S_f} T_i \cdot u_i' dS = \int_V \rho a u_i' dV, \quad \forall u' \in KA
\]

where \( \dot{\varepsilon}_{ij} \) is the stress rate function of actual strain rate, actual stress and unknown constitutive parameters. \( u \) is the virtual strain field calculated from the virtual displacement \( u' \). \( V \) is measured volume, \( \rho, a \) means the density and acceleration respectively. The PVW consists of three terms internal virtual work (IVW), external virtual work (EVW) and acceleration virtual work (AVW). In Equation (3), the
external virtual work term can be eliminated with using proper virtual displacement fields. So only the IVW including stress information and AVW including acceleration information are left in the PVW. Thus the objective function only includes the IVW and AVW. The chosen \( u^* \) was as follows:

\[
u^*_x = 0 \quad \text{and} \quad u^*_y = (y - y_{min})(y - y_{max})
\]

where \( x \) and \( y \) means the horizontal and vertical coordinates in deformed configuration respectively.

2.4. Impact frame high speed tester (IFHS)
Several types of experiments can be conducted to study the dynamic behavior of materials. In this study, a new type of high speed tensile tester, impact frame high speed (IFHS) tester was used for the experiments [3]. Unlike ordinary high strain rate tensile tester, the IFHS utilizes the elastic strain energy. The original IFHS tester was invented for cement fiber specimens and in this study it was modified to use the steel sheet specimens.

When the hydraulic pump pulls the coupler, elastic strain energy is stored in the two energy frame bars. When coupler breaks, the stored energy is converted into kinetic energy to pull the specimen. The number 1 to 7 in Figure 1 means a high speed camera, an elastic energy frame bar, a transmitter bar, a hydraulic motor, a coupler, a lighting system and a specimen respectively.

![Figure 1. IFHS tester set-up for high strain rate tensile test.](image)

3. Simulation
ABAQUS dynamic explicit analysis mode was used for simulation. The objective of simulation was to determine minimum acceleration magnitude for obtaining constitutive parameter with the acceleration information by the VFM. Then, the Johnson-Cook parameter was identified by the VFM based on the simulation results. Finally, two stress-strain curves from the input one and identified one by the VFM were compared.
In order to reproduce real experimental features, the velocity was extracted from the real experiments then this data was applied as a velocity boundary condition for simulations. Figure 2 describes the velocity boundary condition used for the simulation.

![Figure 2. Experimental result based velocity boundary condition.](image-url)

![Figure 3. The IVW and AVW convergence result.](image-url)

![Figure 4. The acceleration data from the simulation.](image-url)
Simulation result proved that constitutive parameter can be identified by the VFM, when sufficient magnitude of acceleration is provided. The objective function which is consist of the IVW and AVW showed good convergence. Figures 3 and 4 show the convergence of the objective function and the amount of acceleration captured from the simulation. In Figure 5, red curve means the curve from the input parameter and green dotted curve is the curve with the parameter identified by the VFM. Finally, Figure 5 verifies that the parameter identified by the VFM using the acceleration is reasonable.

4. Methods to increase the acceleration
The IFHS tester was used for high strain rate tensile test. But, captured magnitude of acceleration was not sufficient for successful identification. Thus, methods to increase acceleration were needed to be applied. In this study, two methods were considered.

4.1. Increase capacity of coupler
When the capacity of coupler increases, the amount of stored elastic strain energy increases naturally. However, it might be lead to unexpected failure of other parts of the IFHS tester. Thus it is not a recommended method.

4.2. Decrease the diameter of an energy frame bar
Two energy frame bars store elastic strain energy when they are pulled by the hydraulic pump. It means that if the stored energy can be increased, the higher impact velocity can be obtained. What is important is that the decreased diameter should be strong enough to bear high tensile load from the motor. The optimized diameter should be carefully selected based on precise calculations.

5. Conclusion
In this study, a method to identify constitutive parameter inversely by the VFM was introduced. The advantage of the VFM in high strain rate case is that the load data is not necessary when sufficient amount of acceleration information can be applied. Simulation result from the ABAQUS verified numerically.
To verify experimentally, the IFHS tester was used. However, with the current setup of the IFHS tester, the magnitude of acceleration was not enough. Therefore, to increase the acceleration magnitude, two possible methods were suggested.

In the presentation, the experimental results will be presented and some aspects for the importance of sufficient acceleration magnitude will be delivered.

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