TENSILE TEST BASED MATERIAL IDENTIFICATION PROGRAM
AFDEX/MAT AND ITS APPLICATION TO TWO NEW PRE-HEAT TREATED
STEELS AND A CONVENTIONAL Cr-Mo STEEL

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A material identification program AFDEX/MAT is presented in this paper. The program is based on
the method for acquiring true stress-strain curves over large range of strains using engineering stress-
strain curves obtained from a tensile test coupled with a finite element analysis. In the method, a
tensile test is analyzed using a rigid-plastic finite element method combined with a perfect analysis
model for its associated simple bar to provide the information of deformation. An initial reference
true stress-strain curve, which predicts the necking point exactly, is modified iteratively to minimize
the difference in tensile force between the experiments and predictions of the tensile test. It was
applied to identifying the mechanical behaviors of two new pre-heat treated steels of ESW95 and
ESW105 and a conventional Cr-Mo steel of SCM435. The predictions are compared with the
experiments for the tensile test of the three materials, showing an excellent similarity.

Keywords: Flow stress; large strain; stress-strain curve; tensile test; pre-heat treated steel.

1. Introduction

A true stress-strain curve is affected by the manufacturing history, metallurgical
treatments, and chemical composition of a material. Therefore, metal-forming simulation
engineers require true stress-strain curves that reflect special conditions of their materials.
However, it is difficult to obtain material properties from experiments and very limited
information about true stress-strain curves can be found in the literature. Most metal
forming simulation engineers use the material properties supplied by software companies,
which are very limited and sometimes unproven.

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It is general that commercial metals show the strain-hardening characteristics during cold working. These characteristics have been being quantified in terms of strain-hardening exponent. At the room temperature, the flow stresses of the common commercial metals are usually represented by the Hollomon’s law, which has been widely used for metal forming simulation. Joun et al. \(^1, 2\) were the first to obtain accurate finite element solutions that satisfied the Considère criterion \(^3\) exactly in an engineering sense using a perfect tensile test analysis model, that is, a cylindrical specimen consisting of a simple bar model without any imperfections. They used the flow stress curve described by the Hollomon’s law with the strain hardening exponent calculated from the true stain at the necking point, which was called a reference stress-strain curve. However, a great deal of discrepancy in tensile load was observed between the predictions and experiments after the necking point when mild steel was examined. To reduce the discrepancy by improving iteratively the true stress-strain curve, Joun et al. \(^4\) presented a finite element method based algorithm of predicting the exact engineering stress-strain curve.

In this paper, a tensile test based material identification program AFDEX/MAT was introduced and applied to identifying the mechanical behaviors of two new pre-heat treated steels of ESW95 and ESW105 \(^5\) as well as a conventional Cr-Mo steel of SCM435.

### 2. Material Identification Algorithm and AFDEX/MAT

Let us first introduce the reference stress-strain curve \(^2\) described by the Hollomon’s law, which is formulated by the strength coefficient \(K\) and strain hardening exponent \(n\), that is, \(\sigma = Ke^n\). The true strain \(\varepsilon_n\) at the necking point in a tensile test of a cylindrical bar for a material is considered as its reference strain hardening exponent \(n_n\) used for describing the reference stress-strain curve, that is, \(n = n_n = \varepsilon_n\). Then the corresponding reference strength coefficient \(K_n\) is calculated by making the reference stress-strain curve predict the true stress at the necking point exactly in simulating the tensile test. Of course, the true stress at the necking point can be obtained from the experiments with the incompressibility condition.

After necking occurs in the tensile test, non-uniformity of the true strain increases rapidly in the longitudinal direction. The maximum strain occurs at the minimum cross-section where the shear stress is free due to symmetry and the non-uniformity of the strain is comparatively low. Therefore, it is relatively easy to define a representative strain at the minimum cross-section.

Through finite element simulation of the tensile test, the minimum cross-section of the tensile test specimen can be traced at a set of \(N\) sampled elongations. The representative strain of the minimum cross-section at the elongation \(\delta = (i = 1, 2, \ldots, N)\), denoted as \(\varepsilon_{\delta}^*\), can be calculated from finite element solutions of the tensile test. The difference between the measured load \(F_i\) and the predicted load \(F_{\delta}^*\) at the elongation \(\delta\) can be reduced by modifying the true stress \(\sigma_{\delta}^*\) corresponding to the representative strain \(\varepsilon_{\delta}^*\), which is defined by the following average area scheme in this study:
\[ \epsilon'_R = \int_{A'} \sigma \, dA / A' \]  

(1)

where \( A' \) indicates the area of the minimum cross-section of the tensile test specimen at the sampled elongation \( \delta' \). The current true stress \( \sigma'_{R,old} = \sigma'_R \) at \( \epsilon'_R \) is modified to give the new true stress \( \sigma'_{R,new} \) by multiplying the current true stress by \( F'_i / F'_e \) as follows:

\[ \sigma'_{R,new} = \sigma'_{R,old} \cdot F'_i / F'_e . \]  

(2)

An iterative algorithm based on the above idea is proposed to obtain an optimized true stress-strain curve. The reference stress-strain curve is used before the necking occurs. After the necking, a true stress-strain relationship is interpolated linearly using the sampled points \( (\epsilon'_R, \sigma'_R) \) defined at the elongation \( \delta' \). The detailed procedure used to calculate the improved sampled points \( (\epsilon'_R, \sigma'_R) \) at the sampled elongation \( \delta' \) is seen in Figure 1. In the algorithm, \( \epsilon'_R \) and \( \sigma'_R \) are the j-times modified strain and stress, respectively, at the sampled elongation \( \delta' \).

More details on the approach can be found from the Reference \(^4\). Based on the proposed algorithm together with the rigid-plastic finite element simulator AFDEX \(^6\), we developed...
a material identification program AFDEX/MAT, which is one of the modules of AFDEX, an intelligent metal forming simulator\(^7\). It needs the diameter and gage length of a cylindrical tensile test specimen and a series of experimental tensile forces at the sampled elongations as the input data. The outputs are either a series of true stresses and strains or the strength coefficients at the sampled elongations. These discrete outputs are interpolated to give the optimized true stress-strain curve.

3. Application to New Pre-Heat Treated Steels and Conventional Cr-Mo Steel

The material identification program AFDEX/MAT was applied to two new pre-heat treated steels of ESW95 and ESW105 and a conventional Cr-Mo steel of SCM435 to reveal their mechanical behaviors. The tensile test specimens were prepared according to the Korean standard for tensile test. The screw grip was adopted to minimize the end effect and to increase the reliability of the tensile test.

Five specimens for each material were tested and a representative tensile test was selected considering the measured yield and tensile strengths. Thus obtained engineering stress-strain curves are shown in Figure 2.

The optimized flow stress curves for ESW95, ESW105 and SCM435 were obtained after five iterations by AFDEX/MAT and are shown in Figure 3. The Cr-Mo steel of SCM435 shows a typical strain-hardening behavior up to the fracture point while the pre-heat treated steels of ESW95 and ESW105 show a typical softening behavior after the strains reach 0.58 and 0.45, respectively.

It is interesting to note that ESW95 and ESW105 have very high initial yield stresses compared with SCM435 and that they do not have the distinct strain-hardening behavior as a whole. As a consequence the flow stress of SCR435 at the strain of 1.5 is nearly the same with that of ESW95 at the initial strain-free state.

The tensile test was simulated for the three materials using AFDEX 2D and the flow stress information depicted in Figure 3. Figure 4 compares the final predicted shapes at
the fracture point, showing that plastic deformation for the pre-heat treated steels takes place only near the necked region. To the contrary, the tensile test specimen of SCM435 was relatively much elongated as a whole before it fractured. Figure 5 compares the predicted and measured engineering strain-stress curves. The comparison shows a close similarity between the experiments and predictions especially for the plastic region, emphasizing the applicability of the material identification program AFDEX/MAT. The maximum error of the predicted load relative to the measured load after the necking point was less than 0.5%. It is interesting to note that the flow stress of SCM435 was calculated up to a relatively high strain of 1.5.

(a) Initial specimen (b) SCM435 (c) ESW95 (d) ESW105

Fig. 4. Predicted deformed shapes with effective strain and metal flow lines at the fracture point.

![Comparison of experiments with predictions of the tensile tests.](image)

Fig. 5. Comparison of experiments with predictions of the tensile tests.
4. Conclusions

A tensile test based material identification program AFDEX/MAT was presented in this paper. The algorithm of the program was based on the method for acquiring true stress-strain curves over large range of strains using engineering stress-strain curves obtained from a tensile test coupled with a finite element analysis. The program was applied to two new pre-heat treated steels of ESW95 and ESW105 and a conventional Cr-Mo steel of SCM435 to reveal their mechanical behaviors involving plastic flow stresses.

It is worthy of emphasizing that the flow stress of SCM435 was calculated up to the considerably high strain of 1.5. In addition, the comparison between experiments and predictions of the tensile test showed very close similarity, revealing the appropriateness of the approach and the applicability of the program AFDEX/MAT.

It has been known from the flow stress information that the initial yield stresses of the pre-heat treated steels tested are quite high but that they have so weak strain-hardening behaviors as to be treated as perfectly plastic materials in the engineering sense. It is believed that their unique feature can contribute not only to reducing the post-work such as straightening and heat treatment but also to minimizing the weight of products in structural design. Of course, it incurs the change of manufacturing process design because their initial yield stresses are considerably high compared to the conventional steels.

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