A Novel Approach for Determination of Hardening Parameters of an Aluminum Alloy under Cyclic Loading with High Amplitudes

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Abstract. An optimization procedure for the determination of combined nonlinear isotropic/kinematic hardening parameters for strain rate-independent cyclic plasticity has been investigated. With this procedure, it is offered that only nine material parameters, including Young’s modulus, yield stress, Poisson’s ratio, two isotropic hardening parameters, and four kinematic hardening parameters, will be sufficient to perform cyclic plasticity analysis with high accuracy in well-known FE programs (e.g. ABAQUS) even for separate strain range amplitudes. The procedure has been performed to calculate such parameters for aluminum alloy EN AW-6082, which is frequently used in vehicle bodies and simulation results are compared with experiment results. The determined parameters lead highly accurate simulation results in FE routines.

1. Introduction
High strength aluminum alloys are used in automotive components frequently [1]. In the most of applications, such components are subjected to cyclic loads, some of which are with high strain amplitudes. Durability of these components may be influenced under different load cases [2]. They may be subjected to initially small number (3-12) of load cycles but with very high amplitude. Then it is required to evaluate the permanent deformation and the crack (breakage of the component) after repetitive high plasticization. In another case, structures may work under further large number of load cycles with small amplitudes after a high plasticization case at the beginning. In this case, by consideration of the history for their plastic deformations, hardening behavior plays a significant role for the further fatigue life calculations and evaluation of permanent deformation. In any case, hardening parameters of the materials should be determined accurately and taken into account in the further durability analysis, which is performed in FE simulations.

In the literature, there exists several investigations presenting procedures to obtain material parameters to be used in the cyclic plasticity applications [3,4]. However, in the most of such investigations [3,5] parameters may be valid only for one strain range amplitude cyclic plasticity applications. These parameters may lead very accurate simulation results for certain strain amplitudes but not for different strain ranges. On the other hand, in some other studies in the literature [4], the material parameters and the theory behind to derive those parameters may not be compatible to well-known FE software (e.g. ABAQUS [6]) and this is impractical in the most of engineering applications. Importance of this issue has been already detected by Badnava et al. [7] and then a generic algorithm has been developed to determine hardening parameters for stainless steel. Furthermore, general
classical mathematical formulation in the literature may be useful for ideal test data (e.g. such as in [8]) however, imperfect [9] or uncharacteristic behavior of such materials require a particular optimization routine to determine accurate material properties [10]. Another issue can be shown as the high number of parameters [11] to use in the evaluation of hysteresis behavior. Decreasing the number of the parameters will be practical in the engineering applications.

Aim of the present study is to develop a model which is capable to describe low cycle fatigue behavior for practical usage on real metallic components (e.g. EN AW-6082). In this model, a novel optimization procedure has been performed for the determination of the combined nonlinear isotropic/kinematic hardening parameters [8,12] for strain rate-independent cyclic plasticity. Only nine material parameters (Young’s modulus, yield stress, Poisson’s ratio, two isotropic hardening parameters, and four kinematic hardening parameters) lead to perform cyclic plasticity simulations in FE programs (e.g. ABAQUS) accurately even for separate strain amplitude ranges.

In the study, firstly hysteresis curves of aluminum alloy specimens have been determined with a uniaxial tension and compression test. Test data has been used to calculate initial isotropic and kinematic hardening parameters by using classical mathematical formulation in the literature. These parameters initiate optimization routines to determine more accurate parameters in FE simulation. Final simulation results are compared with the test data in a hysteresis curve for aluminum alloy EN AW-6082.

2. Experiment
The aim of the experiment is to determine hysteresis curve of aluminum alloy specimens under uniaxial tension and compression loads at room temperature. The experiment has been performed for three different strain amplitudes which are ±1 %, ±3%, and ±5 % under strain controlled test conditions. Cyclic stress-strain curves are established for each specimen by incremental-step method [12] in which the strain amplitude is held constant until its stabilization then the procedure is repeated for the other strain range amplitudes on the same samples. To do so three cycles have been completed at each strain amplitude in a constant quasi-static strain rate for a single specimen. Then the test data is prepared to be used in the following mathematical model effectively.

3. Mathematical Model
Combined nonlinear isotropic/kinematic hardening model [8,12,13] has been calibrated to determine deformation behavior of the structure subjected to cyclic loading in quasi-static loading rate. In order to calculate hardening parameters initially Young’s modulus and initial yield stress at zero plastic strain should be determined from the test data by consideration not only the loading but also unloading regions. Poisson’s ratio is taken as $\nu = 0.33$ for aluminum alloy. Formulation for the isotropic and kinematic hardening models has been followed separately to determine parameters which lead for the initial values of the optimization routines.

In the isotropic hardening model, the change of the size of the yield stress $\sigma^0$ with equivalent plastic strain $\varepsilon^p$ has been defined by

$$\sigma^0 = \sigma_y + Q_\infty \left(1 - e^{-h_{\infty} \varepsilon^p}\right)$$

where $\sigma_y$ is initial yield stress at zero plastic strain. This equation is used to calibrate initial isotropic hardening parameters $Q_\infty$ and $h_{\infty}$ [12]. In this formulation, the test data for one strain range amplitude but each cycle until stabilization are taken into consideration. During the calibration least squared regression has been used.

According to classical kinematic hardening model, Frederick-Armstrong formulation is used to define relationship between stress difference (between maximum tension and compression stresses $\Delta \sigma$) and the corresponding plastic strain differences ($\Delta \varepsilon^p$) at each strain amplitude range [8, 14,15]

$$\Delta \sigma = \sum_{i=1}^{2} \frac{2C_i}{\gamma_i} \tanh \left(\frac{\gamma_i}{2} \Delta \varepsilon^p\right) + 2\sigma_y$$

(2)
where $C_i$ and $\gamma_i$ are kinematic hardening parameters. The formulation has been performed with the consideration of two back stresses ($i:1\rightarrow 2$). It is noted that only one back stress is inaccurate for the fitting but two back stresses are optimum for the accuracy and the number of parameters. During the calibration least squared regression has been used.

The hardening parameters, which have been calculated by the classical mathematical formulation above, are used for the initial estimation in an optimization routine for the determination of more accurate parameters. To do so, optimization routines have been used with least squares error calculations. To accelerate the routines, effect of each particular parameter on the hysteresis curve has been taken into consideration. Parametrization loops in FE model have been performed to determine the most accurate hardening parameters. The results of the FE simulations have been evaluated and compared with the test data, then an error between those results are determined. The optimization routine has been performed to reduce this error. Effects of all material parameters have been evaluated and correspondingly optimum hardening parameters have been determined. Even though the initial parameters which are calculated with the classical mathematical formulation above leads around 40% error, optimized parameters cause to decrease of the corresponding error to 4%.

Figure 1. (a) FE Model, (b) Input displacement at control point A (red line) and axial strain measured between points B and C (blue dashed line)
Material parameters are used in an FE model (parallel to optimization routine) to simulate hysteresis behavior under same loading conditions with the experiment. Three plane symmetries in specimen have been considered as one can see in Figure 1(a). In this figure, point A denotes the control point of the model to apply input displacement, and at each step axial strains between points B and C are measured. To fit the measured strain amplitude with the test data, the input displacement amplitude is rearranged. Hence, strain control conditions have been provided in the FE simulation. Corresponding input displacement amplitude (at point A) and measured strains (between points B and C) are plotted in Figure 1(b).

4. Numerical Results

Young’s modulus $E$, yielding stress $\sigma_y$, isotropic hardening parameters ($Q_\infty$ and $b_{iso}$) and kinematic hardening parameters for two backstresses case ($C_i$ and $\gamma_i$ where $i = 1, 2$) for aluminum EN AW-6082 are calculated first by the classical mathematical formulation and then optimized by using the methodology in the previous sections. Initially calculated material parameters of the material by using classical mathematical formulation have been presented in Table 1.

| $E$ (GPa) | $\sigma_y$ (MPa) | $\nu$ | $Q_\infty$ | $b_{iso}$ | $C_1$ | $\gamma_1$ | $C_2$ | $\gamma_2$ |
|----------|-----------|------|-----------|----------|------|----------|------|----------|
| 66.5     | 227.42    | 0.33 | 27.7      | 88.5     |      |          |      |          |
| 11436.4  | 167.0     |      | 3738.2    | 110.4    |      |          |      |          |

The parameters in this table are used directly in FE simulation to determine initial hysteresis behavior of a test specimen for different strain amplitudes ($\pm$ 1 %, $\pm$ 3%, and $\pm$5%). Result of this simulation and its comparison with the corresponding test result are presented in Figure 2. As one can see in this comparison, the simulation results do not match with the test data, perfectly. Average error between results is around 39 %.

![Figure 2. Comparison of hysteresis curves of test data (blue line) and results of suggested model (red line) for EN AW-6082 with initially determined parameters.](image)

However, optimized material parameters, as given in Table 2, represent relatively better agreement between simulation results and test data as seen in Figure 3. It should be emphasized that average error between simulation and test results for all strain ranges are not higher than 4.2 % in this case.

| $E$ (GPa) | $\sigma_y$ (MPa) | $\nu$ | $Q_\infty$ | $b_{iso}$ | $C_1$ | $\gamma_1$ | $C_2$ | $\gamma_2$ |
|----------|-----------|------|-----------|----------|------|----------|------|----------|
| 66.5     | 245       | 0.33 | 39.54     | 5.03     | 14363.6 | 595.9     | 6031.5 | 103.8    |
5. Conclusion
Nonlinear isotropic and kinematic hardening parameters have been identified by using classical hardening models to determine cyclic plasticity behavior of an aluminum alloy. Then the parameters have been optimized by using a realistic FE simulation in ABAQUS. Finally, simulation results show good agreements with the experiment even though only nine material parameters have been used in the simulations. It should be emphasized that the determined parameters represent accurate responses for both low and high strain amplitudes. It is also noted that the procedure may be applied for any imperfect test data or materials which represent uncharacteristic hysteresis behavior to obtain realistic and accurate FE simulations.

![Figure 3. Comparison of hysteresis curves of test data (blue line) and results of suggested model (red line) for EN AW-6082 with optimized parameters.](image)

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6. References
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