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Nanostructure-based finite element analyses of aluminium profiles subjected to quasi-static axial crushing

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ABSTRACT

In this study, a nanostructure model is used to predict the stress-strain curves of the aluminium alloys AA6063, AA6061 and AA6110 in T6, T7 and O tempers based on the chemical composition and the thermo-mechanical history. The predicted stress-strain curves are then employed in finite element analyses of rectangular hollow section (RHS) profiles of the same materials subjected to axial quasi-static crushing. Thus, the simulations are performed without any calibration of the plasticity model based on material tests. In addition, simulations with the material model calibrated from tensile tests on the same materials are performed for comparison. An experimental programme of the RHS profiles is conducted for validation purposes and compared to the numerical results in terms of the force-displacement curves and the peak and mean forces. To put emphasis on the performance of the nanostructure model, a refined solid element model is used to capture accurately the deformed geometry during axial crushing. A separate study is conducted to investigate the effect of friction on the simulated behaviour of the profiles. The numerical and experimental force-displacement curves display good agreement with deviations in the mean absolute percentage error (MAPE) of the peak and mean force less than 10% and 8%, respectively. By visual inspection of the deformed profiles, excellent agreement is found between the numerical simulations and the experimental tests. The results suggest that the nanostructure model can be used with confidence in design of energy absorbing structural components made of 6xxx aluminium alloys.

1. Introduction

Aluminium is favourable in a number of engineering applications due to its low weight-to-stiffness ratio. Among the many applications are automotive, offshore, protective and aerospace structures. Aluminium alloys have also entered into new application areas during the last several decades due to the development of new alloys with improved properties, often replacing steel as the preferred material. From an environmental point of view, the recyclability of aluminium compared to steel makes it favourable as a future-oriented construction material. In the automotive industry, the introduction of aluminium components has contributed to lower the CO_2 emission and fuel consumption due to weight savings. Other advantageous properties of aluminium include high corrosion resistance, and high electrical and thermal conductivity. Aluminium alloys with specific properties are often required and the possibility to tailor an alloy to given properties would be beneficial.

In 6xxx alloys, the yield strength and the work hardening depend on the chemical composition and the thermo-mechanical history. Nanostructure models able to predict the flow stress from the chemical composition and the thermo-mechanical history of 6xxx alloys have been under development for the last few decades. By use of such models, flow stress curves can be obtained without carrying out any mechanical tests and thus enable simulation-based design of structures made of 6xxx alloys.

The nanostructure model NaMo, which was developed for 6xxx alloys by Myhr et al. [1], has been used with success in different applications on a variety of different alloys. Johnsen et al. [2] conducted ballistic impact experiments on the wrought AA6070 in four different temper conditions. The stress-strain behaviour was predicted by NaMo and used in non-linear finite element simulations with good correlation to the experimental tests. The ballistic limit velocity and the flow stress curves were reported with a maximum deviation of less than 10% between the numerical and experimental results. Holmen et al. [3]

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Table 1
Chemical composition of the different alloys in wt%.

	Si	Mg	Fe	Mn	Ti	Zn	Cu	Cr	Al
AA6063	0.512	0.470	0.206	0.047	0.006	0.003	0.001	0.001	Balance
AA6061	0.621	0.903	0.209	0.038	0.106	0.054	0.204	0.060	Balance
AA6110	0.720	0.828	0.196	0.506	0.026	0.003	0.203	0.157	Balance

conducted experiments on MIG-welded AA6082-T6 extrusions struck by small-arms bullets. A spatial distribution of the stress-strain behaviour at ambient temperature was determined by NaMo from the chemical composition, artificial ageing history and welding procedure. The resulting flow stress curves were functions of the distance from the weld centre line and used in a 3D finite element model to investigate the effect of the heat affected zone (HAZ) on the ballistic properties. The numerical simulations were found to be in good correspondence with the experimental results and the ballistic limit velocities were within 10% of the experimental ones. In Hoang et al. [4], square hollow section AA6060 profiles subjected to quasi-static axial crushing were investigated. The profiles were artificially aged to three different tempers using two different cooling rates after solution heat treatment. The flow stress curves were predicted by NaMo, where the incubation time was included in the simulations by a new feature in the model, and good agreement between the experimental and numerical results was reported. Engler et al. [5] investigated the effect of natural ageing and pre-straining on the strength and anisotropy of AA6016. Tensile tests with varying room temperature storage time and pre-straining were conducted to obtain stress-strain curves for the alloy-temper combinations. Corresponding stress-strain curves were calculated by NaMo and compared to the experimentally obtained ones. It was reported that the curves predicted by NaMo captured the main trends, even though they consistently underestimated the flow stress compared with the measured values.

Crashworthiness of aluminium profiles has been studied extensively in recent years, both experimentally and numerically. The strive to optimize the energy absorbing capability during car crashes has led to studies on a variety of geometries and materials. Zhang et al. [6] studied axial crushing of square multi-cell columns of AA6060-T4. It was found that by introducing internal webs to the columns, the energy absorption capability was improved when comparing plain columns of equal weight. An increased energy absorption efficiency of 50% was reported by substituting a single-cell column with a 3 × 3 column of equal weight. In Zhang et al. [7], square AA6061-O tubes with graded thickness subjected to quasi-static axial loading were investigated experimentally and numerically. Two types of thickness distributions were tested and the results showed that introducing a thickness gradient to a tube might increase the energy absorption capability significantly and an increase in mean force of up to 35% compared to non-graded tubes was reported. However, the problems of material fracture and mode switch were addressed as a potential effect of too excessive grading. The numerical simulations reflected the trends seen in the experiments, and the deviation was less than 16%. Optimization of the tubes was performed by use of the response surface methodology (RSM) to obtain an optimal cross-section for a square tube. Results showed that increasing the wall-thickness in the corners increased the energy absorption capability. Sun et al. [8] studied the energy absorption capability of multi-corner profiles of AA6060 subjected to dynamic axial impact. It was shown numerically that increasing the number and size of corners in a profile had an effect on the energy absorption capability and that multi-corner profiles increased the crushing force efficiency with 12% compared to square tubes of equal weight. Aluminium alloy profiles have also been studied extensively in combination with foam fillers and other reinforcements, see e.g. [9–15].

The main objective of this study is to investigate the accuracy of the nanostructure model NaMo for a range of alloy-temper combinations by employing the predicted stress-strain curves in nonlinear finite element (FE) simulations of RHS profiles subjected to quasi-static axial crushing. To evaluate the accuracy of the flow stress curves predicted by NaMo for application in design of energy absorbing structures, tensile tests and quasi-static axial crushing tests are performed for the same array of alloy-temper combinations. Section 2 presents the alloys and heat treatments, the tensile tests and the axial crushing tests, whereas Section 3 gives an overview of the nanostructure model NaMo and presents the calculated flow stress curves for all combinations of alloy and heat treatment. In Section 4, the FE model of the axial crushing test and the numerical results, obtained with the IMPETUS Afea Solver [16], are presented. The numerical results are discussed in Section 5, and the main observations and conclusions are summarized in Section 6.

2. Experimental study

2.1. Alloys and heat treatments

Three different 6xxx aluminium alloys are investigated in this study: AA6063, AA6061 and AA6110. The alloys were provided by Hydro Aluminium and received as billets with 95 mm diameter and 200 mm length. The chemical composition of the alloys is given in Table 1. The casting length was roughly 1.5 m and the casting conditions were according to standard guidelines for the designated alloys. Prior to extrusion, the ingots were homogenized at 575 °C with a heating rate of 200 °C per hour from room temperature and held for 2 h 15 min before cooling to room temperature at 400 °C per hour. The profiles were extruded as RHS profiles with a wall thickness of 2.8 mm and a cross-section of 37 mm × 29 mm (see Fig. 1), corresponding to a reduction ratio of about 19. The billets were pre-heated to 500 °C before extrusion and the extruded profiles were water-quenched about 0.5 m from the outlet of the die. Approximately the first half meter of the extruded profile for each new alloy was discarded due to possible contaminants in the press. After a short ramp-up time, the ram speed was held constant at 12.1 mm/s for AA6063 and 6.1 mm/s for AA6061 and AA6110. Afterwards, the profiles were cut into lengths of 175 cm and cold-deformed 0.5% by stretching between 1 and 4 h after extrusion. The profiles were then stored at room temperature for 48 h followed by artificial ageing at 185 °C for 8 h to obtain the peak strength temper T6. Selected profiles were further artificially aged to obtain the over-aged temper T7 and the soft annealed temper O, by holding at 185 °C for another 168 h and at 410 °C for 4 h, respectively. Having full control of the chemical composition and the details in the thermo-mechanical history of the material is important for the predictions of the nanostructure model NaMo presented in Section 3.

The profiles were cut into lengths of 100 mm with a geometrical trigger on the two long sides, as shown in Fig. 1, using wire erosion to ensure good repeatability and symmetric progressive folding. This type of geometrical trigger was used with success in Ref. [17] and was accordingly adopted for this study. Prior to testing, the wall thickness of the profiles was measured at various positions and the profiles were weighed.

2.2. Tensile tests

Uniaxial tensile tests were conducted for all nine alloy-temper combinations, using specimens taken from each of the four walls of the

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