Computational Materials Science 79 (2013) 724–735

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

A nano-scale material model applied in finite element analysis of aluminium plates under impact loading

J. Johnsen [a], J.K. Holmen [a], O.R. Myhr [a,b], O.S. Hopperstad [a], T. Børvik [a,c,*]

[a] Structural Impact Laboratory (SIMLab), Centre for Research-Based Innovation (CRI), Department of Structural Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
[b] Hydro Aluminium, Research and Technology Development (RTD), NO-6601 Sunndalsøra, Norway
[c] Norwegian Defence Estates Agency, Research and Development Section, NO-0015 Oslo, Norway

ARTICLE INFO

Article history:
Received 30 March 2013
Received in revised form 13 July 2013
Accepted 26 July 2013
Available online 26 August 2013

Keywords:
Ballistic impact
AA6070
Nano-scale model
Numerical simulations
Experimental validation

ABSTRACT

Finite element simulations of AA6070 aluminium plates struck by ogival-nose projectiles are performed. The aluminium plates are 20 mm thick and heat treated to temper O, T4, T6 and T7. A nano-scale material model, consisting of three parts: a precipitation model, a yield-strength model and a work-hardening model, is used to predict the flow–stress curves of the materials at ambient temperature based on the chemical composition of the alloy and the thermal history defined by the heat treatment. Finite element simulations of the perforation process are then carried out using both 3D solid and 2D axisymmetric elements. The numerically-obtained ballistic limit velocities, predicted without any use of data from mechanical tests, are compared with available experimental data and found to be in good agreement with the experimental ones for all tempers. The same holds for the predicted residual velocities at striking velocities higher than the ballistic limits.

1. Introduction

Age-hardening aluminium alloys are attractive materials for application in lightweight protective structures owing to their high strength-to-weight ratio and good energy absorption capability [1]. The yield strength, work hardening and ductility of these alloys depend on the alloying elements and the heat treatment, but increased strength is usually gained at the expense of lower work hardening and ductility [2]. For a given structural application, it should then be possible, at least in principle, to find an optimal combination of strength, work hardening and ductility by carefully varying the chemical composition of the alloy and the heat treatment. However, if the material properties have to be determined through a number of mechanical tests for each combination, such an approach would be both time consuming and expensive.

Recently, nano-scale material models have been proposed that are capable of predicting with reasonable accuracy the strength [3,4] and work hardening [5,6] of certain classes of age-hardenable aluminium alloys as a function of the chemical composition and heat treatment. The basis for such modelling must be a precipitation model that is sufficiently relevant and comprehensive to deal with non-isothermal heat treatments in an adequate manner. This requires accurate predictions of the decomposition of a solid solution by the formation of a precipitate structure. The precipitation model applied in the present investigation is based on the previous works by Langer and Schwartz [7], Kampmann et al. [8] and Wagner and Kampmann [9] who treat nucleation, growth and coarsening as coupled processes within a framework that is suitable for numerical simulations. The further coupling between the predicted precipitate structure and the resulting yield strength at room temperature can be obtained from established dislocation theory, based on a consideration of the intrinsic resistance to dislocation motion due to solute atoms and particles, as described in numerous publications, see e.g. [10–12].

The final prediction of the resulting work hardening based on a given precipitate structure has been considered by several authors, and the present modelling adopts the basic principles described by Ashby [13], where the total dislocation density is split into statistically stored and geometrically necessary dislocations. This allows a separate treatment of each category of dislocations, where the density of geometrically necessary dislocations can be evaluated from the characteristics of the precipitate structure (i.e. volume fraction and size). The density of the statistically stored dislocations depends on the balance between accumulation and annihilation of dislocations by dynamic recovery as described by Kocks [14] and Mecking and Kocks [15]. Cheng and co-workers [16] combined the basic principles of the Ashby and Kocks models in order to calculate complete stress–strain curves for Al–Mg–Si alloys that

---

* Corresponding author at: Structural Impact Laboratory (SIMLab), Centre for Research-Based Innovation (CRI), Department of Structural Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway. Tel.: + 47 73 59 46 47; fax: + 47 73 59 47 01.

E-mail address: tore.borvik@ntnu.no (T. Børvik).

0927-0256/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.commatsci.2013.07.035

were heat treated to different temper conditions. However, since a precipitation model was not included, this approach cannot be used to predict the resulting stress–strain curve from a given chemical composition and temperature history.

The objective of the current study is to evaluate the possibility of predicting the perforation process and the ballistic limit velocity of AA6070 plates struck by ogival-nose projectiles without using any data from mechanical tests. The nano-scale material model NaMo (Nanostructure Model, see [5,6]) is used to determine the flow–stress curves of the materials based on the chemical composition of the alloy and the thermal history defined by the heat treatment. NaMo consists of three sub-models that are fully integrated in a computer code, i.e. a precipitation model, a yield-strength model and a work-hardening model. The flow–stress curves predicted by NaMo are then used in finite element simulations of the perforation process using both 3D solid and 2D axisymmetric elements.

The results obtained by this approach are validated against an experimental study reported in Holmen et al. [17] on the perforation of 20 mm thick AA6070 plates struck by 7.62 mm AP bullets. The plates were tested in tempers O (annealed), T4 (naturally aged), T6 (peak strength) and T7 (overaged) to study the influence of yield strength, work hardening and ductility on the ballistic limit. In addition to the impact tests, quasi-static tensile tests on these materials were carried out, and used here for the purpose of validating the accuracy of the NaMo simulations. In the impact tests, the dominating failure mode was cavity expansion (also known as ductile hole growth in ballistics) even though some fragmentation occurred, especially for tempers with high strength and low ductility. The fragmentation was most prominent at the highest impact velocities and assumed less important for the ballistic limit. An observation made in the experimental study was that the yield strength is a more important feature than local ductility in ballistic impact for the investigated combination of plate materials, bullet type and impact velocities. It is demonstrated in the following that the agreement between the numerical predictions of the ballistic limit velocities using the proposed approach and the results obtained experimentally is in general good. The study thus shows how it is now possible to conduct finite element simulations of impact-loaded aluminium structures with confidence without any use of data from mechanical tests. Such an approach represents a major advantage in the early design of lightweight protective structures.

The organisation of this paper is as follows. In Section 2, a brief description of the aluminium alloy and the various heat treatments is provided. The theoretical background of NaMo is given in Section 3, while Section 4 presents the results from the NaMo simulations. In Section 5, the finite element modelling is described, and the numerical results are summarised in Section 6. The validation of the proposed approach against available experimental data is presented in Section 7. The modelling assumptions are discussed in Section 8, whereas some conclusions are given in Section 9.

2. Materials

The 20 mm thick target plates of aluminium alloy AA6070 with chemical composition as given in Table 1 were produced by DC-casting and hot-rolling at Hydro's research laboratory in Bonn, Germany. The plates were heat treated to tempers O (annealed), T4 (naturally aged), T6 (peak strength) and T7 (overaged) according to Table 2. The material was characterised by quasi-static tensile tests in different in-plane directions at ambient temperature to determine the yield strength, work hardening, tensile strain to failure and plastic anisotropy, see [17] for details. It was found that the anisotropy in strength and work hardening was negligible, while the tensile strain to failure varied considerably with direction. Typical true stress–strain curves for the 0°, 45° and 90° orientations with respect to the rolling direction of the plate are shown in Fig. 1(a) for the different tempers. The scatter between repeated tests was found to be insignificant. Based on the experimentally-obtained true stress–strain curves, inverse modelling using finite element simulations in combination with an optimisation tool was used to get rid of the pressure component that occurs from necking [17]. The yield stress and the hardening parameters in the constitutive relation were first fitted by a direct calibration to Bridgman-corrected curves from material tests in the rolling direction. These parameters were then used as initial values in LS-OPT, which is an optimisation tool that interacts with LS-DYNA [18]. An axisymmetric finite element model of the tensile specimen was created and several successive analyses were run in sequential order using a hybrid optimisation algorithm with default values. Models with both coarse and fine element meshes were used in the optimisation, but the difference in results was found to be minor. Obtained flow–stress curves in terms of the equivalent von Mises stress versus the equivalent plastic strain for the 0° orientation are shown in Fig. 1(b). It is evident from these figures that the different heat treatments lead to substantial differences in the stress–strain behaviour of the materials, and this will eventually influence the impact resistance of the plates.

The AA6070 plates in different tempers were struck by APM2 bullets fired from a smooth-bore rifle at various impact velocities [17]. The 7.62 mm diameter, 10.5 ± 0.25 g, APM2 bullet consists of a brass jacket, an end cap, lead filler, and a 5 ± 0.25 g, ogive-nose, hard steel core with a diameter of 6.17 mm. The steel core has a density of 7850 kg/m^3, hardness HRC of 63, and a calibre–radius–head of 3. More information regarding the bullet materials can be found in Børvik et al. [19].

Table 1
Chemical composition (in weight%) of aluminium alloy AA6070.

Al	Si	Fe	Cu	Mn	Mg	Others
Balance	1.38	0.22	0.26	0.54	1.23	0.15

3. Theoretical outline of NaMo

Fig. 2 describes the components of the nano-scale material model NaMo which is a combined precipitation, yield strength and work hardening model for age-hardening aluminium alloys [5,6]. The present version is comprehensively verified and validated for 6xxx series aluminium alloys (see e.g. [4–6,20–22]), but the basic principles and the mathematical framework are expected to be applicable also for other alloy systems like 2xxx and 7xxx alloys. The three sub-models shown in Fig. 2 are fully integrated in a computer code, where the outputs from the precipitation model

Table 2
Heat treatment processes of AA6070 to obtain the different tempers.

Temper	Solutionizing	Cooling	Annealing/artificial aging	Cooling
O	90 min at 560 °C	Water quench	24 h at 350 °C	Slow cooling
T4	90 min at 560 °C	Water quench	–	–
T6	90 min at 560 °C	Water quench	64 h at 160 °C	Slow cooling
T7	90 min at 560 °C	Water quench	8 h at 200 °C	Slow cooling