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Flow behaviour of Nickel Aluminium Bronze under hot deformation

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ABSTRACT

Flow behaviour of a Nickel Aluminium Bronze (NAB) alloy under hot compressive deformation was investigated using a deformation dilatometer. Temperatures of 1023, 1073, 1123 and 1173 K and strain rates of 0.1, 1.0 and 10 s^{-1} were used as the forming parameters. The experimental results showed that true stress–strain curves of the alloy exhibited dynamic recovery and dynamic recrystallisation with single-peak stress. Dynamic recovery was dominant at higher temperature and lower strain rate. The peak stress increased as the strain rate and temperature increased. The peak strain also increased with increasing strain rate. However, it was independent of temperature. The flow curves can be represented by the hyperbolic-sine law Arrhenius equation with activation energy of 514.25 kJ/mol. Comparisons between predicted flow stresses and experimentally determined results showed that the developed constitutive models were sufficiently accurate to demonstrate flow behaviour at high temperatures of the NAB alloy. This was supported by a correlation coefficient R of 0.981 and an average relative error of 13.42% for the particular test conditions. Dynamic material modelling approach has been used to describe flow stability/instability. For the NAB alloy, the criterion of the strain rate sensitivity, the criterion with regard to the variation of strain rate sensitivity with $\log \dot{\varepsilon}$ and the criterion of the temperature sensitivity were always satisfied. The critical criterion is the rate of change of the temperature sensitivity with respect to $\log \dot{\varepsilon}$.

1. Introduction

Nickel Aluminium Bronze (NAB) is a copper based alloy containing nominally 9–12% Al, 6% Ni and 3–5% Fe. NAB alloy is extensively used for marine applications such as ship propellers, valves and bearings [1]. The advantages of NAB alloy are high strength, high ductility, high fracture toughness and excellent corrosion resistance, especially when in seawater applications [2–5]. The microstructures of most NAB alloys consist of Cu-rich solid solution of α phase, various kinds of inter-metallic phases collectively referred to as κ phase and some β' phase. Microstructure, and hence optimum mechanical and corrosion behaviour, is controlled by chemical composition of the NAB alloy and the corresponding thermo-mechanical history during manufacturing processes. The plastic deformation of these alloys is thermally activated at elevated temperatures ($T > 0.5T_m$) [6]. As an alternative to casting, hot forging is the common fabrication method for large and complex metallic parts especially in marine applications. In recent years, several investigations have been carried out on casted and wrought NAB alloys but have mainly focused on microstructural variations after heat treatment and related corrosion properties [1–5]. However, there is no previous study regarding the flow behaviour of the NAB alloy. Therefore, understanding of deformation behaviour and flow characteristic at high temperature of the NAB alloy is necessary for part designers and manufacturers. The relationship between flow stress, strain rate, strain and temperature is normally associated with the activation energy of the material [6–9].

Constitutive equations have been often used to describe plastic flow properties of metals and alloys in order to understand working processes in relation to the prevailing loading conditions [7]. Both hardening and softening mechanisms of materials are significantly influenced by the forming temperature and applied strain rate. During hot deformation, alloys undergo both work

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hardening and softening. Dynamic softening mechanisms such as dynamic recovery (DRV) and dynamic recrystallisation (DRX) mostly occur in metals with high stacking fault energy, for example, aluminium alloys [9]. Copper has low stacking fault energy [9], which is associated with DRV behaviour. Most of the copper alloys reported in literature are said to show DRV only [10,11]. However, some copper alloys, for example Cu–6% Al [12], also show DRV and DRX with single-peak stress. DRX with multiple-peak stress is not been observed in Cu alloy. There are some reports regarding high temperature deformation behaviour and the dynamic softening of aluminium alloys [13,14]. Softening mechanisms and microstructure evolution were dependent on temperature, degree of deformation and strain rate. The flow stress increased with increasing strain rate and decreasing forming temperature [15,16]. The phenomenon of decreasing flow stress can be shown in term of flow softening, which can be related to dynamic recrystallisation, temperature rise and flow instability as will be discussed further using dynamic material modelling approach [17]. In addition, the flow stress under hot deformation behaviour of functional graded material can also be modelled using the Zener–Hollomon equation and a phase mixture law and boundary layer properties [18]. Good fatigue properties are also important for NAB alloy especially when it is used as ship propellers and bearings. However, there have been limited studies on NAB alloy. The high cycle fatigue behaviour of Cu–Be alloys was studied [19] providing a criterion for the fatigue assent based on the strain energy density [20].

The aim of this study was to determine the influence of strain, strain rate and temperature on the compressive deformation characteristics of NAB alloy using a deformation dilatometer at various temperatures and strain rates. Constitutive equations relating flow stress, deformation temperature and strain were applied to obtain corresponding material parameters. The peak flow stresses predicted by the constitutive equations were compared with the experimental results. Finally, the flow stability was investigated using a dynamic material modelling approach.

2. Experimental procedures

The material investigated in this work was an as-cast NAB alloy provided by the Royal Thai Naval Dockyard Department. The chemical composition of the NAB alloy was determined by X-Ray Fluorescence spectrometry (XRF) and is given in Table 1. All as-cast NAB ingots were firstly homogenised at a temperature of 948 K for 6 h and subsequently cooled down in air [3]. The homogenised ingots were machined for hot compression tests. The compression specimens were cylindrical with a diameter of 5 mm and a height of 10 mm as shown in Fig. 1(a). Each specimen contained a recess with a diameter of 4 mm and a height of 0.3 mm at both ends to act as a reservoir for molybdenum lubricant, which was used to minimise friction between the specimen and push rods during hot compression.

A deformation dilatometer as illustrated in Fig. 1(b) was used for inductive heating, compressing and cooling the test specimens. In this work, uniaxial compression tests at different isothermal temperatures were performed at temperatures of 1023, 1073, 1123 and 1173 K and strain rates of 0.1, 1 and 10 s^{-1}. It is noted that the solidus point (T_m) of the investigated NAB alloy was measured at 1333 K and the hot deformation temperatures were well above 0.5 T_m, which is 666 K.

Before deformation, each specimen was initially heated up to the deformation temperature with a heating rate of 10 K/s and held for 60 s in order to obtain a homogeneous temperature distribution throughout the specimen. All test specimens were compressed up to a true strain of 0.92 (equivalent to a height reduction of 60%). After deformation, the samples were directly quenched using argon gas with a cooling rate of 6 K/s. The thermo-mechanical process schedule applied for the specimens is shown in Fig. 2. Force and displacement data were collected during the tests and they were converted to true stress–strain curves. For all tests, temperatures of the samples were measured on the surface at the middle of the specimen by an attached thermocouple.

Table 1
Chemical composition of the investigated NAB alloy.

NAB	Chemical composition (wt%)				
	Al	Ni	Fe	Mn	Cu
As cast	9.26	3.26	2.55	0.22	Balance

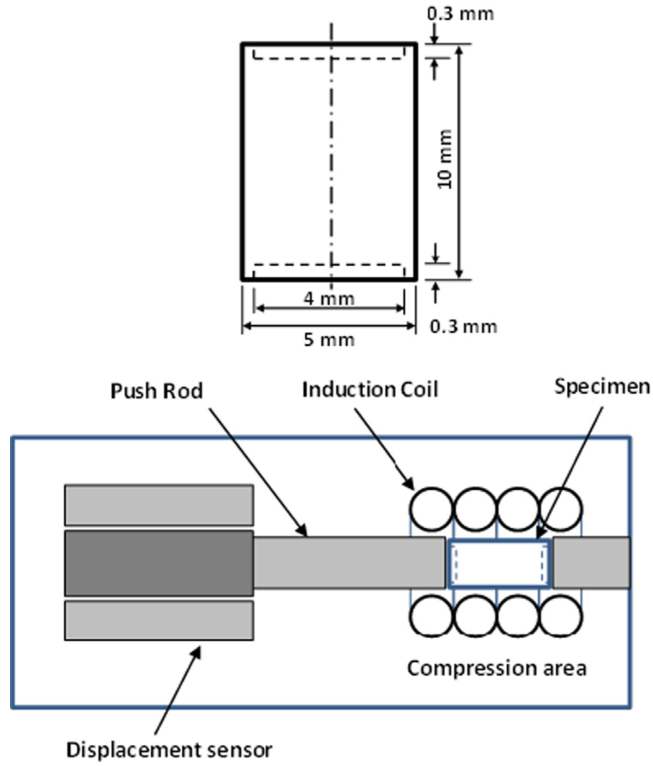

Fig. 1. (a) Specimen for hot compression test and (b) schematic of the deformation dilatometer.

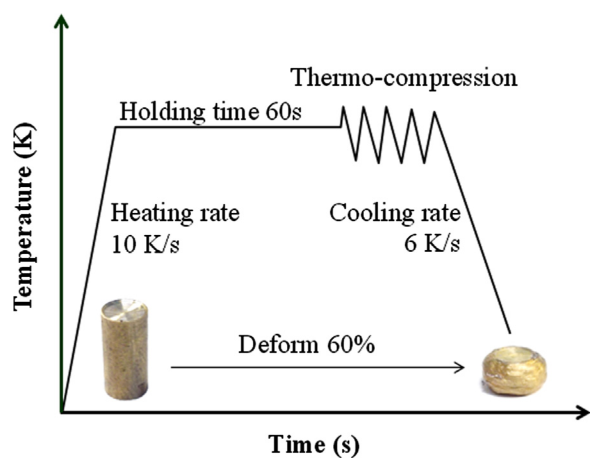

Fig. 2. Temperature–time profile of hot compression tests.