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Formability evaluation for sheet metals under hot stamping conditions by a novel biaxial testing system and a new materials model

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ABSTRACT

Hot stamping and cold die quenching has been developed in forming complex shaped structural components of metals. The aim of this study is the first attempt to develop unified viscoplastic damage constitutive equations to describe the thermo-mechanical response of the metal and to predict the formability of the metal for hot stamping applications. Effects of parameters in the damage evolution equation on the predicted forming limit curves were investigated. Test facilities and methods need to be established to obtain experimental formability data of metals in order to determine and verify constitutive equations. However, conventional experimental approaches used to determine forming limit diagrams (FLDs) of sheet metals under different linear strain paths are not applicable to hot stamping conditions due to the requirements of rapid heating and cooling processes prior to forming. A novel planar biaxial testing system was proposed before and was improved and used in this work for formability tests of aluminium alloy 6082 at various temperatures, strain rates and strain paths after heating, soaking and rapid cooling processes. The key dimensions and features of cruciform specimens adopted for the determination of forming limits under various strain paths were developed, optimised and verified based on the previous designs and the determined heating and cooling method [1]. The digital image correlation (DIC) system was adopted to record strain fields of a specimen throughout the deformation history. Material constants in constitutive equations were determined from the formability test results of AA6082 for the prediction of forming limits of alloys under hot stamping conditions. This research, for the first time, enabled forming limit data of an alloy to be generated at various temperatures, strain rates and strain paths and forming limits to be predicted under hot stamping conditions.

1. Introduction

In automotive and aircraft industries, weight reduction can directly reduce energy consumption, which is beneficial to fuel economy improvement and environmental friendliness [2]. A 10% decrease in the mass of a conventional vehicle results in a 6%to 8% decrease in fuel consumption rate without compromising vehicle's performance [3]. Two feasible ways for reducing the weight of automobile structures are the use of high strength steel and the use of sheet of low density. At room temperature, high strength steel and aluminium alloys have low formability, which leads to high springback and poor surface quality of formed components. To deal with this problem, warm and hot forming technologies have been developed, which are hot stamping and cold die quenching (also termed as press hardening) for quenchable steel [4] and solution heat treatment, forming and in-die quenching (HFQ®) of lightweight alloys [5]. The hot stamping and cold die quenching process, abbreviated to hot stamping, is used to obtain shapes with great complexity and relatively high strength in automotive applications. In hot stamping process, heat treatable metal blank is heated up in a furnace, transferred to a press and subsequently formed and quenched in a cold tool [6]. The technique can be applied to both boron steel and low density sheet metals, such as aluminium alloys [7] and magnesium alloys [8]. It has been formulated as the HFQ® process, to form complex shaped parts for lightweight structure of vehicles. In the HFQ® process, a metal sheet is heated up to a specific temperature at which it is a solid solution with a single phase and then transferred to the press and subsequently formed and quenched in the cold tool [9,10]. The control of forming conditions, such as heating rate, soaking time, cooling rate, forming temperature and strain rate, is critical for the success of these processes [11].

The forming limit diagram (FLD) is commonly used to evaluate the formability of sheet metals [12]. An FLD comprises a set of forming limit curve which identifies the boundary between uniform deformation and the beginning of plastic instability which leads to materials

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failure. According to the definition of an FLD, strain paths are described as proportional [13], from uniaxial through plane strain to equi-biaxial. The characteristic of path dependence causes an FLD to be invalid under non-proportional loading [14]. The FLD of a material at elevated temperatures varies greatly in terms of shape and position from one formed at room temperature. At an isothermal testing condition, proportional strain paths and constant strain rates are required for the determination of FLDs at elevated temperatures. Formability tests are used to obtain FLDs for sheet metals experimentally and two types of test method are conventionally used to determine forming limit strains, namely the out-of-plane test and the in-plane test. Nakazima test is a typical out-of-plane test [15], specimens with different widths are stretched by a hemispherical punch or hydraulic pressure [16]. Using multiaxial tube expansion test is an effective out-of-plane method to measure forming limits under various strain states and stress states [17]. The out-of-plane test at room temperature has been standardised. It has been used to obtain FLDs at elevated temperature as well [18]. Ayres et al. [19] investigated the effects of temperature and strain rate on the formability of AA5182 at a temperature of 130 °C and 200 °C. Bagheriasl [20] used cartridge heater for heating up the die in Nakazima test in order to obtain the FLDs of AA3003 at temperature of 100–350 °C and strain rate of 0.003–0.1/s. The digital image correlation (DIC) technique [21] was adopted for strain measurement during the tests. Min et al. [22] performed the formability test at a temperature of 800 °C for boron steel to determine the left hand side of an FLD for hot stamping applications, but deformation temperature cannot be controlled accurately due to the transfer stage of specimen from a furnace to the cold tool. Shao et al. [23] determined FLDs for AA5754 at various temperatures (200–300 °C) and forming speeds (20–300 mm/s) by setting up the test tool in a hot furnace to create an isothermal environment. In order to simulate HFQ® conditions, the requirement to simultaneously form and quench after heating makes testing in a furnace impractical. In the in-plane test, such as the Marciniak test [24], the test material is stretched over a flat-bottomed punch of cylindrical/elliptical cross section. A carrier blank with a central hole is usually used to avoid frictional contact between the sheet metal specimen and the punch, but optimising the dimension and geometries of carrier blank and punch is required in order to induce strain localisation and cracking in the unsupported region of the specimen, which complicates the test procedure and increases the cost of testing. Li and Ghosh [25] carried out a formability test of aluminium alloys 5754, 5182 and 6111 by using the Marciniak approach at a rapid forming rate of 1/s and a range of temperature of 200–350 °C, but data was not obtained at temperatures over 350 °C. Naka et al. [26] investigated the effects of forming speed (0.2–200 mm/min corresponding to strain rate of 0.0001–0.1/s) and temperature (20–300 °C) on forming limits for AA5083 by using a heated punch in the in-plane test. Planar tensile test utilising a tensile machine with a cruciform specimen is an alternative method to determine forming limits of a material. Hannon and Tiernan [27] reviewed planar biaxial testing systems for sheet metals. Two types of test machines are generally used, i.e. standalone biaxial tensile test machines and link mechanism attachments in uniaxial test machines for biaxial testing. Leotoing et al. [28] improved a cruciform specimen for the use of formability tests and determined the FLD of AA5086 at room temperature [29]. A servo-hydraulic biaxial testing machine was used to control loading paths in two vertical directions [30]. A better linearity of strain path can be obtained by a planar biaxial testing machine compared to conventional Nakazima and Marciniak tests. Abu-Farha et al. [31] investigate biaxial deformation of AA5083 and AZ31 at 300 °C by using a designed testing tool and a heat gun based on an INSTRON uniaxial tensile test machine.

However, neither of the out-of-plane and the in-plane methods discussed above for determining forming limits are suitable for hot stamping applications because extra heating and cooling devices are needed and control of heating rate, cooling rate, deformation temperature and stretching strain rate is difficult to obtain precisely. Therefore, a formability testing system was proposed previously to determine FLDs of alloys experimentally under hot stamping conditions.

Experimentally determining formability is time-consuming and costly, which restricts the number of tests that may be conducted. Because of that, various analytical and numerical models have been developing as an alternative to perform theoretical formability prediction and eliminate the need for much experimental work. Banabic et al. [32] and Stoughton et al. [33] reviewed primary models for forming limit prediction at room temperature from four aspects, namely new constitutive equations used for limit strain computation, polycrystalline models, ductile damage models, advanced numerical models for nonlinear strain paths or various process parameters. Theoretical models applied to FLD prediction at elevated temperature include Hora's theory [34,35], M-K theory [24,36,37] and Storen and Rice's theory Rice [22,38,39]. Although various analytical and numerical models have been developed for theoretical formability prediction, most of them are applicable to ambient conditions or warm/hot forming conditions. Viscoplasticity theory can also be used for analysis on forming processes at elevated temperatures and a dislocation-based viscoplastic-damage model had been proposed by Lin et al. [40] since microstructural evolution at elevated temperatures has a great effect on formability of an alloy. This theory can be developed to predict forming limits of metals for hot stamping applications [41].

The goal of this paper is to employ improved biaxial test system and optimised specimens to enable experimental data of FLDs of an alloy, for the first time, to be determined under hot stamping conditions, and to be used for calibration of materials model. A novel planar biaxial testing system for use on a Gleeble thermo-mechanical simulator is presented first in this paper to obtain FLDs of AA6082 under HFQ® conditions. Formability tests of AA6082 were conducted at various temperatures, strain rates and strain paths after heating and cooling processes. A 2D continuum damage mechanics (CDM)-based material model was developed for the prediction of forming limit of alloys under HFQ® conditions and the constitutive equations were calibrated and validated from the formability test results of AA6082.

2. Experimental programme

2.1. Temperature profile

Hot stamping conditions contain the control of heating rate, soaking time, cooling rate, deformation temperature and strain rate. Aluminium alloy 6082, which is extensively used in the automotive industry [42], was used to machine the specimens to conduct the formability tests under HFQ® conditions. Chemical composition of commercial AA6082 at T6 condition is shown in Table 1. The determination of FLDs requires the deformation of the specimen to be performed at constant temperature and constant strain rate under different linear strain paths. A schematic of the required temperature profile for formability tests of AA6082 under HFQ® conditions is shown in Fig. 1. Heating rate and cooling rate are critical parameters for the HFQ® process and should be controlled precisely to maintain a supersaturated solid solution without grain degradation in a specimen. The material of AA6082 was heated to the solution heat treatment temperature of 535 °C [43] at a heating rate of 30 °C/s, soaked for 1 min, which was sufficient for full resolution of precipitates, and then quenched to a designated temperature in the range of 370–510 °C at a cooling rate of 100 °C/s [44]. The tensile tests

Table 1
Chemical composition of AA6082 .

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Weight proportion (%)	0.90	0.38	0.08	0.42	0.70	0.02	0.05	0.03	Balance

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