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Prediction of flow curves and forming limit curves of Mg alloy thin sheets using ANN-based models

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ABSTRACT

Multivariable empirical models based on artificial neural networks were developed in order to predict the flow curves and forming limit curves of AZ31 magnesium alloy thin sheets, in warm forming conditions, vs. process parameters and fibre orientation. Experimental tensile and hemispherical punch tests were carried out in order to obtain the experimental data set, in terms of flow curves and forming limit curves, to be used to train the artificial neural networks. A preliminary study, based on the leave one-out-cross validation methodology, has proven the very good predictive capability of the ANN-based models in modelling both flow curves (flow stress level, curve shape and strain at the onset of necking) and forming limit curves (curve shape, major strain values and minor strain limit) under different process conditions and fibre orientations. Then, the generalisation capability of the neural models in capturing the effect of process parameters and fibre orientation on flow curves and formability has been proven by the excellent agreement, in terms of the high correlation coefficients, low relative errors and average absolute relative errors, between predicted and experimental results not investigated in the training set.

1. Introduction

In most of the manufacturing industries, the knowledge in the field of environmental sustainability is still insufficient, mainly due to the need of a proper modelling of sustainability factors to be taken into account [1–4]. In this context, many opportunities, such as selection of "environmental-friendly" materials, waste minimisation, energy efficiency and end-of life strategies, can be taken into account in order to design sustainable products. Some researches proposed a new sustainability framework identified as 6R concept (Recover, Reuse, Recycle, Redesign, Reduce, and Remanufacture). The basic idea is that different design elements are associated with the life cycle of a product, and multi-life cycles can be associated with a single product. Environmental requirements can then be introduced to anyone of the development stages by applying various tools and methodologies. By integrating environmental requirements at various stages of a product manufacture, the concept of sustainable development can be applied [5].

As far as the automotive industry is concerned, the effects of problems related to the gas emissions and their influences on local air quality in urban areas, global warming, the treatment of vehicles at their end of life and other environmental topics, are becoming a must. By considering the environmental effect caused by vehicles, the main contribution that can be given in reducing fuel consumption and exhaust emission levels is related to weight reduction. To this purpose, in the latest years, much attention was paid to lightweight materials that, unlike the conventional steels, can offer a high potential in car weight reduction due to their low densities. About the end-of-life of a vehicle, some aspects on material recycle have to be taken into account, such as material waste reduction, energy savings in secondary material production, recyclability of materials, innovative forming processes able to recycle materials [1–3].

Among the lightweight materials, magnesium alloys are receiving increasing attention owing to their high strength to weight ratio. Several studies have shown that some steel components of chassis, interior and body structure of car can be replaced with magnesium alloy ones. A further benefit offered by magnesium is its high recyclability [6]. Magnesium, however, exhibits low deformability at room temperature due to its hcp structure, even though an increase in temperature activates additional slip systems at the microstructural level, thus improving the attitude to undergo plastic deformation. Furthermore, under such conditions, Mg alloys can undergo dynamic recrystallisation (DRX) by which deformed grains are replaced by new undeformed grains that nucleate and grow until the original ones have been entirely replaced. Such microstructural mechanism is accompanied by a reduction in the flow stress and plastic anisotropy, and by an increase in formability [7–15].

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Table 1
Scheme and training parameters of the ANN-based models for flow curve prediction.

	Strain at the onset of necking model	Flow stress model
Number of input nodes	$3(\dot{\varepsilon}, T, fo)$	$7(\varepsilon, \dot{\varepsilon}, T, fo, \ln(\dot{\varepsilon}), \ln(\varepsilon), 1/T)$
Number of output nodes	1 (ε_n)	1 (σ)
Number of hidden layers	1	1
Number of hidden nodes	3	7
Activation function input-hidden layers	Tanh	Tanh
Activation function hidden layers-output	Linear	Linear
Distribution of weights	Gaussian	Gaussian
Momentum coefficient	0.1	0.1
Learning coefficient	0.9	0.9

Table 2
Topology and training parameters of the ANN-based models for forming limit curve prediction.

	Minor strain model	FLC model
Number of input nodes	4 (T, s, fo, $S_{\varepsilon 2}$)	4 (T, s, fo, ε_2)
Number of output nodes	1 ($\varepsilon_{2\text{lim}}$)	1 (ε_1)
Number of hidden layers	1	1
Number of hidden nodes	4	4
Activation function input-hidden layers	Tanh	Tanh
Activation function hidden layers-output	Tanh	Linear
Distribution of weights	Uniform	Gaussian
Momentum coefficient	0.1	0.1
Learning coefficient	0.4	0.9

Unfortunately, forming operations performed at high temperature suffer of low sustainability and high costs. Scientific literature reports that the best compromise among formability, costs and sustainability can be obtained as sheets forming operations of Mg alloys are performed in the temperature range from 200 to 300 °C [7]. The obtaining of the very complex shapes, however, requires the application of virtual prototyping techniques. To this purpose, reliable and versatile computer-aided-engineering (CAE) softwares are available in order to accurately and efficiently predict events processes are subjected to. The validity of the process simulations is strongly dependent on the input data, such as the rheological behaviour and formability. In spite of the necessity to perform experimental investigations required to obtain the input data and the need to build virtual prototypes, such approach is very attractive since it allows the reduction in the number of physical prototypes and, consequently, leads to the reduction in the design and development costs, and in the time to market.

As far as the rheological behaviour of metals under deformation is concerned, it can be predicted using empirical analytical, physically-based and empirical non-analytical models [16]. Among the empirical non-analytical models, the artificial neural network (ANN)-based ones are the most widely used since they do not require a priori knowledge of the mechanisms operating during deformation; furthermore, they do not need to use complex mathematically explicit equations or computer simulation techniques in inverse analyses [16]. ANNs have been studied for many years in order to solve problems that require a large amount of processing with the same human ability [17–22]. Several works have been performed on the application of ANNs to model the flow behaviour in sheet metals considering the effect on flow stress of process parameters such as strain, strain rate and temperature [23–32]. However, the influence of the fibre orientation on flow stress has scarcely investigated. A further aspect that has not still investigated in detail concerns the development of models able to predict the effect of the process parameters and fibre orientation on ductility (i.e. the strain at the onset of necking), required in order to evaluate the strain domain of the flow curves.

As far as the sheet formability is considered, the forming limit curve (FLC), giving the relationship between the major strain and minor strain at the onset of necking, are generally used in order to represent the ease with which a sheet metal can be shaped through plastic deformation; in particular, the FLC provides the strain domain for safe deep drawing, stretch forming or combinations of both as a function of the process parameters and fibre orientation [15]. Modelling of FLCs is not traditionally investigated so that very few results can be found in literature [33,34]. A further aspect that is not usually taken into account is the effect of process parameters and fibre orientation on the minor strain interval within which the forming limit curves develop. However, the ANN can represent a powerful tool to model the forming limit curves under warm forming conditions.

In this context, the present investigation focused on the development of multivariable empirical models based on artificial neural networks, able to predict the flow curves and forming limit curves of AZ31 magnesium alloy thin sheets in warm forming conditions, against the process conditions and fibre orientation. A preliminary study, based on the leave one-out-cross validation methodology, has proven the very good predictive capability of the ANN-based models in modelling both flow curves (flow stress level, curve shape and strain at the onset of necking) and forming limit curves (curve shape, major strain values and minor strain limit) under different process conditions and fibre orientation. The ability of ANN-based model in capturing the effect of process parameters and fibre orientation on flow curves and formability was also evaluated by comparing the experimental curves, obtained under process conditions not investigated in the training data set, with the predicted ones. The excellent performances given by the ANN-based models have been also confirmed by the low values of the relative error and average absolute relative error, and by the high values of correlation coefficients.

2. Material and experimental tests

2.1. Material

The material used in the present investigation was AZ31 magnesium alloy, supplied in form of 1 mm thick sheets, commonly used in stamping processes for the obtaining of components for aerospace, automotive and electronic industries [35,36].

2.2. Tensile tests

The plastic flow behaviour of AZ31 magnesium alloy was investigated by means of uniaxial tensile tests. The trials were performed at a constant nominal temperature in the range from 200 to 300 °C, with constant strain rates within the interval from 0.001 to 1 s^{-1}. The flow curves at a strain rate of 1 s^{-1} were corrected in order to take into account the temperature increase due to the deformation heating, according to the procedure described by De Sanctis et al. [37]. The specimens were machined both with the loading direction parallel (RD) and perpendicular (TD) to the rolling one [15].

2.3. Hemispherical punch tests

The forming limit curves of AZ31magnesium alloy were obtained by hemispherical punch tests carried out at a constant