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On the significance to use dislocation-density-related constitutive equations to correlate strain hardening with microstructure of metallic alloys: The case of conventional and austempered ductile irons

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ABSTRACT

In order to highlight the importance of selecting the proper constitutive equation of plastic flow in metallic alloys, the strain hardening behaviours of conventional (DI) and austempered ductile irons (ADI) with similar hardness were investigated as study-case. The empirical Hollomon equation and the dislocation-density-related Voce equation were compared. Hollomon equation showed strong limitations in describing the different strain hardening behaviours of DIs and ADIs. Conversely, Voce equation approximated properly all the flow curves, and Voce parameters could describe successfully the different strain hardening behaviours of the two groups of alloys. Voce parameters, rationalised by the Kocks-Mecking-Estrin physical concepts, could also give an insight to the micro-mechanisms that underlie strain hardening, like dislocation density multiplication, dynamic recovery and microstructure features that affect these micro-mechanisms during straining. Through the analysis of Voce parameters it could be highlighted that the DIs strain hardening behaviour was mainly caused by the fine pearlitic structure, consisting of ferritic lamellae with sub-micrometric widths. The improvement of austempered alloys in strength and ductility was related to a significantly lower propensity of ADIs to recover dynamically, which was mainly attributed to the dual phase structure of these alloys. Furthermore, the strain hardening analysis through Voce formalism could identify in ADIs a critical condition of strain hardening rate to be investigated to improve further their ductility, which could not be found with Hollomon equation. The dislocation-density-related Voce equation describes properly the strain hardening behaviour of metallic alloys and give certain correlations between strain hardening behaviour and microstructure.

1. Introduction

Production routes of commercial alloys are often characterized by solid state transformations. Strain hardening is very sensitive to microstructure and, therefore, strain hardening analysis is a powerful tool to study microstructure evolution during production processes. One of the most significant example is the determination of the initiation of dynamic recrystallisation in alloys deformed at high temperatures according to the widely-used method of inflection point of strain hardening rate [1]. In works focussed on correlating strain hardening and microstructure, empirical equations like Hollomon and Hollomon-type equations with no physical meaning [2–5] have been often fitted to the experimental flow curves and the trends of the characteristic parameters of these equations are correlated to the process conditions or chemical compositions. However, this is an improper procedure, since strain hardening analysis should be first performed by studying the experimental strain hardening rate ($d\sigma/d\varepsilon_p$) vs. flow stress (σ) with ε_p the plastic strain, and then an opportune constitutive equation should be selected to fit the flow curves [2,6–9]. In this way, other constitutive equations could appear more adequate than the empirical Hollomon-type equations to describe the plastic behaviour of alloys. There are indeed constitutive equations that have physical meaning, like the dislocation-density-related constitutive

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equations [6–9], where their characteristic parameters can be correlated directly to alloys microstructure and micro-mechanisms of plasticity. Therefore, these equations are potentially more useful to characterize metallic alloys and their microstructure.

The Hollomon-type constitutive equations (Hollomon, Swift, Ludwik and Ludwigson) are power law relationships between σ and $\varepsilon_{p.}$ Hollomon equation is the most widely used for its simplicity, that is

$$\sigma = K \cdot \varepsilon_p^n \tag{1}$$

K is the strength coefficient and n is the strain hardening exponent. The Hollomon parameters K and n can be easily found through plotting the experimental data $\sigma - \varepsilon_p$ in a log–log plot. Dislocation-density related constitutive equations are exponential decay relationships between σ and ε_p [6–9]. Voce equation [10] is the simplest of these equations and is defined as

$$\sigma = \sigma_V + (\sigma_o - \sigma_V) \cdot \exp(- \varepsilon_p / \varepsilon_c) \tag{2}$$

σ_V is the saturation stress that is achieved asymptotically with plastic straining, ε_c is the characteristic strain that defines the velocity with which σ_V is achieved and σ_o is the back-extrapolated stress to $\varepsilon_p = 0$. Actually, the saturation stress is never achieved during tensile tests because of the specimen instability due to necking. Therefore, σ_V is an ideal value that can be used to compare materials when Voce equation is used to model flow curves. The differential form of Voce equation is a linear relationship between $\mathrm{d}\sigma/\mathrm{d}\varepsilon_p$ and σ, since

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon_p} = \frac{\sigma_V}{\varepsilon_c} - \frac{1}{\varepsilon_c}\sigma \tag{3}$$

So, if linear regions in the experimental data strain hardening rate ($\mathrm{d}\sigma/\mathrm{d}\varepsilon_p$) vs. flow stress ($\sigma$) are found, Eq. (3) is used to find the Voce parameters ε_c and σ_V, and Voce equation can fit properly the flow curves. There is a significant benefit in using Voce equation, since it can give an insight into the relationship between strain hardening and microstructure. In fact, although Voce equation was originally proposed as an empirical equation in 1948 [10], later Kocks and Mecking [6,7], and Estrin [8,9] gave physical meaning to the differential form of Voce equation in Eq. (3), through relating the Voce parameters ε_c and σ_V to the micro-mechanisms underlying plastic deformation, like dislocation density multiplication, dislocation density reduction through dynamic recovery and microstructure features affecting these micro-mechanisms, as reported also in austenitic stainless steels [11,12]. The case of ductile irons is quite significant, since completely different microstructures in these alloys of similar compositions can be obtained through different heat treatments and solid transformations. The results of analysing the plastic behaviours of ductile irons through the Hollomon and the Voce equations are reported to compare the capabilities of these two kinds of equations to describe strain hardening and correlate strain hardening behaviour with microstructure.

Conventional Ductile Irons (DI) identify a group of alloys that contains limited percentages of alloying elements (mainly C, Si and minor Cu, Mn and Mg) to provide a microstructure characterized by graphite with nodular shape. The application of DIs in engineering components is widely used for their good combination of fine mechanical properties and economic return of their industrial production over irons and steels [13,14]. As increasing strength and toughness of DIs have been required, chemical compositions and production routes have been widely investigated to obtain different microstructures and good mechanical properties [15–17]. Depending on the conventional ductile iron grade the microstructure can be fully ferritic, ferritic-pearlitic or fully pearlitic. Ferritic matrix with graphite nodules results in good ductility, impact resistance, tensile and yield strength. Pearlitic matrix provides higher strength, better wear resistance with moderate ductility and impact resistance. Ferritic-pearlitic structure presents intermediate mechanical properties with good strength and toughness [18–20]. Isothermed ductile irons (IDI) [21] are characterised by perferritic structure, where ferrite and pearlite are interconnected instead of having the conventional “bulls-eye” shape. This structure is obtained through austenitizing low alloyed ductile irons in the intercritical range of temperatures where only part of the matrix transforms into austenite [22]. The interconnection improves strength and ductility with respect to conventional DIs with similar hardness.

Austempered Ductile Irons (ADI) are produced through austempering conventional ductile irons. Austempering consists of austenitizing in the range 850–890 °C and isothermally holding the alloys in salt bath at temperatures typically between 250 and 400 °C, where the austenite decomposes resulting in a microstructure of acicular α ferritic-bainitic Widmanstätten plates, metastable γ_{HC} austenite with high carbon content, and graphite nodules dispersed in the $\alpha + \gamma_{HC}$ matrix [23–25]. These alloys exhibit an outstanding combination of high strength, ductility, toughness and fatigue strength [23,26,27] and due to their superior mechanical properties, many engineering components such as gears and crankshafts have been recently produced in ADIs [28,29]. Investigating plastic behaviour of these materials is necessary to rationalize their general mechanical properties, like wear and low cycle fatigue [30–34]. It has recently underlined [22] that there is a significant gap between the potential and the actual applications of DIs, and this gap has been attributed to a conservative approach regarding the material properties, particularly for perferritic IDIs and upper ausferritic ADIs. In order to fill this gap, the plastic behaviour analysis cannot be limited to determine engineering parameters, as yield stress (YS), ultimate tensile strength (UTS) and elongation to fracture (L_F), but the strain hardening behaviour of materials (or the shape of the flow curves) has to be analysed deeply, correlating possibly strain hardening and microstructure. Strain hardening analysis has been used to characterize the products of different austempering processes [35–37]. However, in these works on ADIs the strain hardening analysis has been carried out only by using empirical equations, like Hollomon and Hollomon-type equations [30–37]. In Ref. [38] Hollomon, Ludwigson and also Voce equations were used to fit the tensile flow curves of compacted graphite cast irons at elevated temperatures, but the work was focused on the comparison of the capability of these equations in approximating the experimental flow curves, but no proper analysis of strain hardening based directly on microstructural aspects was carried out.

The first part of the present work is focused on the comparison between the procedures of analysis of the plastic behaviours of conventional and austempered ductile irons with Hollomon and Voce equations, focusing on the capabilities of the equations to approximate flow curves and particularly to describe the relevant differences in strain hardening behaviours of DIs and ADIs with similar hardness. In the second part, the physical interpretation of the Voce parameters based on mechanistic equation of strain hardening proposed by Kocks-Mecking-Estrin was used to rationalise the significantly different strain hardening behaviours of conventional and austempered ductile irons.

2. Theoretical background

2.1. Physical meaning of Voce equation

In FCC and BCC metals with hard obstacles to dislocation