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Alloy design by dislocation engineering

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ABSTRACT

Ultra-high strength alloys with good ductility are ideal materials for lightweight structural application in various industries. However, improving the strength of alloys frequently results in a reduction in ductility, which is known as the strength-ductility trade-off in metallic materials. Current alloy design strategies for improving the ductility of ultra-high strength alloys mainly focus on the selection of alloy composition (atomic length scale) or manipulating ultra-fine and nano-grained microstructure (grain length scale). The intermediate length scale between atomic and grain scales is the dislocation length scale. A new alloy design concept based on such dislocation length scale, namely dislocation engineering, is illustrated in the present work. This dislocation engineering concept has been successfully substantiated by the design and fabrication of a deformed and partitioned (D&P) steel with a yield strength of 2.2 GPa and an uniform elongation of 16%. In this D&P steel, high dislocation density can not only increase strength but also improve ductility. High dislocation density is mainly responsible for the improved yield strength through dislocation forest hardening, whilst the improved ductility is achieved by the glide of intensive mobile dislocations and well-controlled transformation-induced plasticity (TRIP) effect, both of which are governed by the high dislocation density resulting from warm rolling and martensitic transformation during cold rolling. In addition, the present work proposes for the first time to apply such dislocation engineering concept to the quenching and partitioning (Q&P) steel by incorporating a warm rolling process prior to the quenching step, with an aim to improve simultaneously the strength and ductility of the Q&P steel. It is believed that dislocation engineering provides a new promising alloy design strategy for producing novel strong and ductile alloys.

1. Introduction

Generally, high-performance alloys require ultrahigh strength as well as good ductility, as strength and ductility are the two important mechanical properties that determine their applications in various industries. Unfortunately, strength and ductility are often mutually exclusive, and producing ultra-high strength metallic materials with good ductility remains to date challenging [1]. It has been well documented in literature that alloys can be strengthened by various strengthening mechanisms which are briefly reviewed as follows. The first strengthening mechanism is *solid-solution strengthening*. Both substitutional and interstitial solid solutions can be employed to increase the yield strength (YS) of an alloy as they can provide extra resistance stress for dislocation glide [2]. Solid-solution has been a traditional strengthening mechanism widely used in many alloys [2]. Recently, solid-solution strengthening has found a new application in high entropy alloys [3–5], which in general have a high percentage of multiple substitutional atoms [3]. The second strengthening mechanism is *precipitation strengthening*. The strength of the alloy depends on the size and volume fraction of the precipitates, as precipitates act as barriers for dislocation glide. In general, there is an optimum size at which the strength can be maximized. Precipitation strengthening has been widely used in Al alloys [6–8], high strength low alloy (HSLA) steels [9], maraging steels [10,11], and recently developed ferritic steels [12,13]. The third strengthening mechanism is *dislocation strengthening*. The YS increases with the dislocation density in an alloy following the well-known Taylor hardening law [14]. Dislocation strengthening has been applied to cold-formed steels and other alloys [2]. The forth strengthening mechanism is *grain refinement*. The dependence of YS on grain size can be described by the well-known Hall-Petch relation [15,16]. As a result, reducing the grain size to the nanometre scale has recently received much attention. For instance, severe plastic deformation (SPD), such as high pressure torsion (HPT), equal-channel angular pressing (ECAP), and accumulated roll-bonding (ARB), have been applied

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