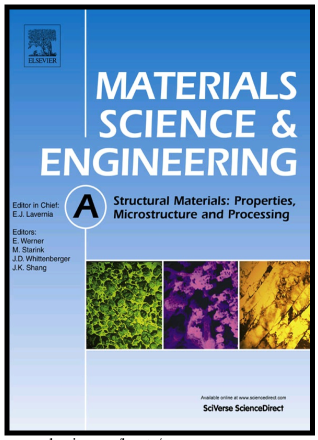

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Abstract

In this work, a CALPHAD thermodynamic model is used to assess the thermodynamic stability of austenite in an Ultra-High Strength Martensitic Steel (i.e., Eglin Steel) in order to refine parent austenite-grain sizes, via high temperature equal-channel angular pressing (ECAP). The parent austenite-grain sizes are reduced from 188 µm to 14.8 µm, which in turn, led to the refinement of martensite lath sizes. This approach produced a yield strength of 1.68 GPa, ultimate strength of 1.98 GPa, and an elongation of 16.1%. Overall, this method reduced development cycle times and achieved alloy performance on par with Ni-Co secondary hardening steels.

Keywords: CALPHAD, Ultra-High Strength Steel, Equal Channel Angular Pressing, Grain Refinement, Martensitic Steel

1. Introduction

Ultra-High Strength Steels (UHSS) have garnered vast amounts of interest for their utility in mining [1] (e.g., drill bits, pipes, and structural materials), the automobile industry [2] (e.g., gears and frames), and in various aerospace applications [3] (e.g., landing gears). In particular, UHSSs offer enhanced strength (i.e., typically yield strengths, σ_Y, in excess of 1.38 GPa) with reasonable ductility (e.g., elongations at failure, ε_f, greater than 10%) [2]. Many alloys have been developed that meet these criteria [2], with some of the more common alloys being AerMet-100, HP-9-4-30, and AF1410, which require considerable amounts of alloying elements (see Table 1 for composition and typical properties) that can make widespread use cost prohibitive. As such, other high strength Ni-Cr-Mo martensitic alloys like 4335V have attracted significant interest, offering high performance with fewer elemental additions.

In the last decade, a new multicomponent Fe-Cr-Si-W-Mo UHSS developed by the U.S. Air Force Research Laboratory (AFRL) has emerged, also known as Eglin Steel (ES-1). ES-1 is a martensitic steel, which is strengthened by the semi-coherent precipitation of ε-carbide. The steel can achieve a 1.59 GPa minimum ultimate tensile strength, σ_{UTS}, and a 1.24 GPa minimum σ_Y through heat treatment alone, and it is also capable of achieving high low-temperature impact toughnesses (i.e., with more than 54 N-m of toughness at - 40˚C), which sets it apart from the aforementioned high strength martensitic alloys (e.g., 4335V). Despite the higher impact toughness and great hardenability of ES-1, its quasi-static tensile properties are only comparable to that of 4335V, falling short of the properties of the Ni-Co intermediate alloyed secondary hardening UHSSs, making ES-1 only practical for specific dynamic applications. As such, the desired goal is to reduce the performance gap between stage one tempering alloys in the class of ES-1 and the heavily alloyed Ni-Co secondary hardening UHSSs, while minimizing elemental additions.

Given the obvious difficulties in changing the composition of an alloy in order to improve performance, the clear choice is to enhance the properties through processing. Additionally, current conventional heat treatment procedures call for very high austenitizing temperatures (i.e., 1160˚C), which leads to undesirable grain growth and further reductions in properties (e.g., toughness [4] and σ_y [5]). There are many processing options available that can circumvent this issue and potentially increase the σ_{UTS} (e.g., via cold forming processes [6]), but the vast majority of them lead to an undesired reduction in cross sectional area and can significantly reduce the ductility, introduce anisotropy, and lead to cracking. In order to preserve initial material dimensions, Severe Plastic Deformation (SPD) methods were considered in this alloy development effort. Through SPD, high levels of strain can be introduced into the base material with little observed change in cross-sectional area [7]. In particular, Equal Channel Angular Pressing