ABSTRACT

The growing demand for fuel-efficient and environmentally sustainable automobiles has accelerated the development of advanced lightweight steels. The medium Mn steel emerges as a potential solution to the automobile industries owing to its light weight and superior strength-ductility synergy. Importantly, the alloying elements play a crucial role in tailoring the constituent phases which may finally leads to better mechanical properties. Among various alloying elements, Ni plays a significant role in stabilizing austenite, tailoring multiphase microstructure, promoting precipitates (NiAl) and thereby improving the mechanical properties of lightweight steels. However, the development of cost-effective multiphase lightweight steels remains limited, as most lightweight steels developed so far for automotive applications are predominantly austenite-based. In view of this, the present study is focused on the development of novel Ni-modified medium manganese multiphase lightweight steel (Ni-MLS) for automotive applications. Further, the study also elucidates the intrinsic mechanical properties and local deformation behavior of the Ni-MLS. Firstly, Ni-MLS with ~7 wt.% Mn (Ni-MLS7) is developed employing melting-casting technique. The Ni-MLS7 is observed to be failed during hot-forging within a temperature range of 1273 K to 1373 K. Therefore, in order to tailor more balanced microstructure and avoid material failure during thermo-mechanical processing (TMP), the nano-scale mechanical response and the local deformation behavior is explored in Ni-MLS7. Towards this, nano-indentation tests are carried out in Ni-MLS7 specimens at homogenized (undeformed) and forged (deformed) condition. The maximum shear stress for elastic to plastic transition (τ_{max}) is evaluated from the nano-indentation data by applying Hertzian theory. The τ_{max} is found to be higher (∼7.2 GPa) in the undeformed specimen in comparison to the deformed one (∼4.2 GPa). Further, the activation volume (Ω_v) is calculated in order to understand the nature of dislocation nucleation. The Ω_v of deformed specimen is observed to be higher as compared to the undeformed specimen. The results suggest that the dislocation nucleation mechanism in the undeformed specimen is governed by the nucleation of fresh dislocations under the indenter tip. However, the dislocation nucleation in deformed specimen is predominantly attributed to the multiplication of pre-existing dislocations. The distinct variation in τ_{max} and Ω_v in both the specimens could be related to the complex microstructural features, such as various precipitates and phases. Therefore, in order to understand the influence of microstructural features on the nano-scale mechanical properties, the nano-hardness of individual phases and different regions across the microstructure such as grain boundary (GB) and interphase boundaries are evaluated and correlated with microstructural features. The nano-hardness is observed to be higher in both BCC ($\sim 10.3 \pm 0.9$ GPa) and FCC ($\sim 9.9 \pm 0.9$ GPa) phases of undeformed specimen in comparison to the deformed one, which predominantly indicates the influence of nano-sized precipitates on the nano-hardness. Conversely, the GB and the interphase region in deformed specimen show a higher nano-hardness ($\sim 13 \pm 0.8$ GPa and $\sim 10 \pm 1.3$ GPa in BCC and FCC, respectively) than the undeformed specimen due to the presence of coarser precipitates

along GB and interphase. The higher nano-hardness of GB and interphase region could act as a potential site for crack propagation and may leads to material failure. So, these GB and interphase precipitates must be eliminated in order to avoid material failure. Therefore, the study suggests that the further alloy development should be based on the appropriate selection of alloying elements in order to suppress the formation of coarse interphase and GB precipitates. In addition, the TMP routes should be carefully optimized to regulate interphase and GB precipitations. Towards this, a new Ni-MLS has further been developed by reducing the alloying content such as C (< 0.2 wt.%), Al (< 6 wt.%) and Mn (< 6 wt.%) in order to eliminate the interphase precipitations. Further, TMP has been precisely scheduled to avoid the GB and interphase precipitates and the microstructure – texture – property correlation is established in the optimized Ni-MLS with ~5 wt.% Mn (Ni-MLS5). It is observed that the hot-rolled Ni-MLS5 specimens after annealing at 873 K (HR-873A), 973 K (HR-973A), and 1073 K (HR-1073A) exhibit multiphase microstructure (retained austenite (R_A), martensite and ferrite). Therefore, the complex interplay between the microstructure evolution and tensile properties in a Ni-MLS5 following hot rolling and annealing is established. It has been observed that the coexistence of recrystallized and deformed grains has resulted in superior tensile properties in the HR-973A specimen (UTS = 1130 ± 26 MPa, elongation = 25 ± 1.5 %), as compared to the other specimens. Further, the smaller grain size, the presence of martensite twins and higher fraction of high angle grain boundaries in HR-973A specimen contribute significantly to enhance its tensile properties. Importantly, the higher transformation induced plasticity (TRIP) effect leads to improved tensile property in HR-973A specimen as compared to other specimens. Additionally, the higher intensity of γ-fiber in BCC and α-fiber in FCC contributes to an improved balance of strength-ductility in the HR-973A specimen in comparison to other HR-annealed specimens. Further, to improve the tensile properties of HR-973A specimen, cold rolling (CR) and subsequent annealing at different temperatures viz., 973 K (CR973A), 1073 K (CR1073A), 1173 K (CR1173A) have been carried out. The multiphase microstructure encompassing ferrite, austenite and martensite is observed in all the CR-annealed specimens. In addition, B2 (NiAl) precipitates have been observed within the ferrite matrix of CR973A specimen. In contrast, the presence of annealing twins has been observed within the austenite matrix of CR1073A specimen. The CR1073A specimen exhibits superior tensile strength (UTS = 990 ± 28 MPa) with high ductility (50 ± 1.6%) as compared to the other CR-annealed specimens. The strength-ductility product (i.e., strength × ductility) of CR1073A specimen is ~50000 MPa% which surpasses the tensile property of most of the recently developed 3rd generation advanced high strength steels, as reported in literature. The excellent strength-ductility synergy in CR1073A specimen is attributed to the presence of multiphase microstructure, optimum grain size of austenite and ferrite, co-occurrence of recrystallized and deformed grains, presence of annealing twins as well as more efficient TRIP and twining induced plasticity (TWIP) effects. Overall, the present study provides important insights into nano-scale deformation behavior, dislocation activities, precipitation characteristics, and microstructure-texture-property correlations in Ni-modified multiphase lightweight steels. The findings establish a novel approach to

develop of next-generation multiphase lightweight steels with superior mechanical performance through appropriate alloy design and thermo-mechanical processing optimization, thereby opening new avenues for advanced automotive structural applications."

Keywords: Activation volume; B2 (NiAl); Dislocation nucleation; Multiphase micro-structure; Micro-texture; Nano-indentation; Ni-modified medium Mn steel; Onset of plasticity; Phase transformation; Recrystallization; Strain hardening response; Tensile properties; Thermo-mechanical processing; TRIP effect; TWIP effect.