Abstract

This thesis deals with understanding the deformation behaviour of various grades of high-performance steel in different length scales, starting from the bulk (large-scale) to the level of slip (small-scale). One of the purposes of this study is to elucidate the factors that govern the deformation and determine the bulk mechanical properties. Further, it is known that the deformation micromechanism is distinct from the bulk due to the intrinsic and extrinsic factors, and the deformation features also change depending on the length scale. Therefore, this work articulates these phenomena in a multiapproach.

In this regard, three different compositions have been chosen for the experiment based on their crystal structure i.e. ferritic (body-centred cubic) and austenitic (face-centred cubic). A ~24 mm thick plate of API X80 grade linepipe steel (bcc) consisted of various morphologies of ferrite and bainite, and martensite-austenite constituents was subjected to bulk deformation by room temperature cold-bending operation, replicating the initial step of a pipe-forming process followed industrially. The subsequent alteration of mechanical properties and their anisotropy which are not understood profoundly so far have been studied through experiments and finite element simulation. Interestingly, cold-bending improves both strength and impact toughness at room temperature and -80°C, respectively. Mechanical property anisotropy is found to decrease near the surfaces (inner and outer), especially on the outer surface throughout the temperature regime between -80°C to 20°C. Different factors operating at different temperature regimes improve the impact toughness. Room temperature impact toughness improves near the inner surface, especially parallel to the rolling direction of the plate, owing to the compressive residual stress attributed

to bending. Whereas, crystallographic texture and the density of cleavage crack initiation sites come into play at -80°C.

To study the effect of grain size on the deformation mechanism and also cut down the number of microstructural variables, an almost fully austenitic (fcc) stainless steel grade 301L was 87% cold-rolled obtaining deformation-induced martensite and annealed subsequently attaining fine/ultrafine-grained austenitic microstructure. Under tensile deformation, initially, the ultra-fine grains (< 1 μm) exhibit deformation-induced transformation, followed by comparatively coarser grains (1.5 – 5.0 μm). Thermodynamic calculations envisage that the reduction in grain size is equivalent to an increase in indigenous stacking fault energy. Thus, the formation of both deformation twin and ε-martensite is likely in ultrafine grains, while the coarser grains facilitate only ε-martensite formation. These two act as the precursors to α′-martensite forming at a higher strain, and therefore, the total amount of transformed product is more in ultrafine-grained material after tensile failure. About the crystallographic texture, the Copper {112}<111> and S {123}<634> orientations predicted by Visco-plastic self-consistent modelling, were not obtained practically under tensile deformation as they preferentially transformed to martensite due to the development of high stress concentration associated with lower slip activity (low Schmid factor).

On the other hand, the local scale deformation produced by nanoindentation load is found to be significantly different from the bulk deformation. During loading, a high population of grain boundaries restrict the dislocation motion most efficiently, and during unloading, the dislocation pile-ups at the boundaries release back stress facilitating the elastic recovery. Coarser grains, in contrast, do not exhibit significant pile-up and eventually a lesser recovery. Nevertheless, low-angle boundaries interact more with the dislocations, allowing a few to pass through, resulting in such a defect structure that the strain locally reaches the critical value for the formation of deformation-induced martensite following the Kurdjomov-Sachs orientation relationship.

Orientation dependence of local deformation behaviour of stable austenitic grade SS 304 is studied rigorously through nanoindentation experiments, crystal plasticity criteria, and molecular dynamics simulation. The experimental findings are in line with the simulated results. Grains with the plane normal $[\bar{1}\bar{1}\bar{1}]$ have the highest hardness in SS 304 steel i.e. most effectively restrict the dislocation motion inside the grain interior from beneath the indentation, followed by the ones with the planes' normal $[\bar{1}\bar{1}0]$ and $[\bar{1}00]$. The alignment of the slip planes relative to the indentation loading vector plays a pivotal role in dictating the shear/slip accommodation. The viscoplastic slip criterion determines that the more the number of slip systems exhibiting shear/slip (even if small), the deformation is more likely to be accommodated. The dislocation lines are mostly Shockley partials (1/6<112>) forming loops by their interaction. Each loop, consisting of two pairs of sessile locks i.e. Stair-rod 1/6<110> and Hirth 1/3<001> dislocations, grows by its edge segments and gets pinched off from the source in the shape of prismatic loops. This phenomenon is governed by the "lasso" or extended-"lasso" mechanism by the attraction and annihilation of the screw segments, inducing back stress and leading to load dips i.e. plastic recovery, especially in (111) oriented grains.

Keywords: Bulk deformation behaviour; Local deformation behaviour; Nanoindentation; Microstructure; Crystallographic texture; Steels; Slip; Deformation-induced transformation.