Chapter 9

Major Conclusions

9.1 Major conclusion: take away of the current research

The main objective of the present study is to thoroughly understand the microstructural changes of S1 and S2 low-density steels during its MAF and their relationships to the material's mechanical properties. The last few decades have witnessed numerous attempts from various researchers to enhance the mechanical property of Fe-Mn-Al-C low-density steel by thermomechanical treatment or SPD technique and explain the mechanisms associated with the remarkable behaviour of these steels. Similarly, the author has also tried to study and fill up the research void in understanding the structure-property relationship during MAF of the investigated steels. Both experimental as well as FE simulation results have been presented. In the process, the author have developed two different low-density steels (S1 and S2 steel) and strained the material by MAF procedure. The influences of some of the important strengthening mechanisms such as grain boundary strengthening and dislocation strengthening on the strength and ductility are examined in the current work. The valuable understandings obtained from this research work are summarized as follows:

- After solutionization and WQ, Fe-30Mn-9Al-0.8C exhibits a fully austenitic microstructure, referred as austenitic low-density steel. Meanwhile, Fe-20Mn-10Al-1C displays an austenitic microstructure with 5% ferritic content, known as duplex steel.
- The current material (S1 and S2 steels) possesses very high ductility than the other Fe-Mn-Al-C low-density steels or the conventional steel and may readily be cold forged, and thereby, it can save money and time as compared to those of hot forging.

- The developed J-C constitutive model produces a fairly accurate and precise estimation of flow stress with a good correlation to experimental data under various strain rates and temperature conditions. Therefore, the proposed J-C constitutive model may confidently be utilized to simulate FE model of any other plastic deformation process such as machining, rolling, punching, and deep drawing and their performance can be assessed in advance.
- During the MAF process, the Fe-30Mn-9Al-0.8C steel undergoes 5 passes before failing, whereas the Fe-20Mn-10Al-1C steel only withstands two passes before failing due to the lower ductility of the latter.
- The refinement of austenite grain size is only possible from 50 μm to 13 μm in Fe-30Mn-9Al-0.8C steel, whereas in Fe-20Mn-10Al-1C steel, the grain size reduces only from 80 μm to 40 μm.
- Through MAF, the yield strength is increased by 4 times and the ultimate tensile strength is doubled for Fe-30Mn-9Al-0.8C steel, whereas for Fe-20Mn-10Al-1C steel, the yield strength is enhanced by 1.5 times and the ultimate tensile strength is increased by 1.8 times.
- Both grain refinement and dislocation density contribute to yield strength significantly during MAF of the Fe-30Mn-9Al-0.8C low-density steel at 250°C. Contribution to YS from dislocation density dominates over grain refinement in early stages (1 to 3 passes). However, the degree of grain boundary strengthening is more than that of dislocation strengthening at later stages (3 to 5 passes).
- The FE model of MAF incorporating the modified J-C material model agrees well with the experimental results and predicts dislocation density distribution, grain size and yield strength at every pass of MAF. Therefore, the proposed modified J-C model may also be confidently used for other cold deformation processes.

- Up to MAF-3, friction induces compressive residual stress, which mitigates crack flow. Beyond MAF-3, tensile residual stress develops between the surface and core, so heat treatment is needed after MAF-3 to reduce tensile stress and allow more passes.

9.2 Future directions

The present study mostly deals with the development of high ductile low-density steels (S1 and S2) and enhancement of strength of these steels through MAF. A microstructure based modified J-C constitutive model incorporating the effect of grain size and dislocation density has been developed to predict the yield strength of material. However, from the scientific understanding and industrial point of view, the certain areas are still remained unexplored in the present investigation. Therefore, the current investigation can be extended in the following directions:

- The strain rate during the thermomechanical processing and the following heat treatment plays an important role in the fraction of recrystallized austenite grains. So, it is necessary to observe the microstructure and tensile property of S1 and S2 steels at higher solutionization temperatures (above 1050 °C).
- The change in microstructure and mechanical property of S1 and S2 steels may vary when conducting MAF at different temperatures and strain rates. Future studies may consider incorporating the effect of temperature and strain rates on dislocation density and grain size evolution during the MAF process.
- The author has not incorporated annealing the sample after each MAF pass, which could significantly impact the evolution of dislocation density and grain size. The selected compositions could multiaxially forged for more passes by incorporating intermediate heat treatment to get ultrafine grain. Furthermore, annealing could relieve the dislocations and more MAF pass could be possible.

- Experimental technique other than XRD can be adopted to measure residual stresses inside the material.
- The modified J-C model predicted lower yield strength through FEM as compared to the experimental values. So, incorporating microstructure behaviour such as hardening behaviour and texture effect at higher strain level is required.
- Fracture/damage model can be developed to predict the failure of the material during MAF process.