PREFACE

This work has investigated mechanical properties of Fe-30Mn-9Al-0.8C (S1) and Fe-20Mn-10Al-1C (S2) low-density steels before and after multiaxial forging (MAF). The selected composition of Fe-Mn-Al-C steels possesses numerous industrial applications due to their high strength-to-weight ratio with high ductility. The microstructural changes in selected low-density steels during MAF and their impact on tensile strengthening have been thoroughly investigated. MAF is a complex deformation process involving multiple mechanisms operating at both micro and macro scales. The presence of closed die walls in MAF restricts the flow of plastic material, placing the specimen under triaxial stress. This results in simultaneous, localized plastic strain variations across different regions, leading to an internal stress distribution. Therefore, finite element modelling is essential for understanding the plastic behaviour and predicting residual stress distribution during forging. First, the low-density steel has been prepared in our laboratory. The material compositions are optimally chosen to yield the best ductility (>70%) with good tensile strength. Ingots of 2.5 kg of S1 and S2 (each) alloys have been prepared by vacuum induction melting process in combination with argon atmosphere. The cast ingots have been homogenized at 1200℃ for 2 hours, and then they are hot forged for 60% deformation, between 1200℃- 900℃ with intermediate heating and finally quenched in water maintained at room temperature. The forged S1 and S2 steels are solutionized at 1050℃ for 1 hour, and water quenched (WQ) and these are designated as SS1and SS2 steels, respectively. Tensile specimens and MAF workpiece have been machined from SS1 and SS2 steels. Tensile tests have been performed at strain rates of 10^{-4}, 10^{-3}, 10^{-2}, and 10^{-1} s^{-1}, and at various temperatures such as 150°C, 300°C, and 450°C before MAF. MAF is carried out at 250°C and a normal strain of 33% is imposed to workpiece. The SS1 steel has completed 5 passes (with an equivalent strain of 2.3) and failed in 6th pass while SS2 steel has completed only 2 passes (with an equivalent strain of 0.92) and failed in 3rd pass. Each multiaxially forged workpiece is characterized by optical microscopy, X-ray diffraction (XRD) and electron backscattered diffraction (EBSD), tensile test, and hardness. XRD method is also utilized to measure surface residual stresses.

Johnson-Cook (J-C) model is formulated to predict the flow stress behaviour of SS1 low-density steel. Tensile test data at quasi-static, moderate strain rate and temperature conditions are used to determine the characteristic parameters of J-C model. The reliability of the J-C parameters has further been improved by using genetic algorithm (GA) based optimization technique. Thereafter, using the improved J-C constitutive equation, numerical simulation (using ABAQUS explicit software) is performed for two different tensile tests and the simulation results are compared with the experimental stress-strain curves. Additionally, a numerical framework is developed to model the evolution of dislocation density, grain size and yield strength at each stage of MAF. To emphasize the role of strengthening parameters in predicting the flow stresses in every MAF pass accurately, a material VUMAT subroutine in ABAQUS has been created for a modified J-C constitutive model that accounts for the role of increased dislocation density and reduced grain size. Finite element method (FEM) has also been used for computing the residual stresses across the volume for SS1 low-density steel during MAF.

After solutionization and water quenching, S1 has fully austenitic microstructure called as austenitic low-density steel while S2 has austenitic with 5% ferritic microstructure called as duplex steel. The selected compositions have achieved high total elongation greater than 70%. However, austenitic one has higher uniform elongation. The yield strength of SS2 steel is 1.5 times greater than that of SS1 steel due to presence of ferrite in prior one.

MAF up to equivalent stain of 2.3 for the selected austenitic steel reduces the grain size from 50 μm to 13 μm. MAF of duplex steel reduces the grain size from 80 μm to 40 μm.

After successfully completing five passes of MAF, the yield strength increases 4 times in austenitic steel while the same increases 2.4 times for duplex steel. The tensile strength of the austenitic low-density steel increases from 762 to 1548 MPa. However, this enhancement is accompanied by a significant reduction in ductility, declining from 64% to 0.8%. Similarly, duplex low-density steel increases the tensile strength from 821 to 1474 MPa in two passes with decrease in ductility from 60% to 2%. Both grain refinement and dislocation density contribute to yield strength significantly during MAF of the selected low-density steels at 250°C. Contribution to yield strength from dislocation density dominates over grain refinement during MAF 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 SS1 steel has positive strain rate sensitivity and has highest ductility at 300^0C. The optimized J-C model constants by GA appear to be closer (with error 4.9%) to reality as compared to the curve fitted J-C model constants (with error 14.98%). Correlation coefficient for lower strain rate and for lower temperature is higher (99% each) compared to the same for higher strain rate and higher temperature (87% and 76%, respectively). The finite element (FE) model of MAF incorporating the modified J-C material model agrees well with the experimental prediction of evolution of 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. At the top surface, the normal residual stress components exhibit a compressive trend, with maximum magnitude in the 1st pass, decreasing in 3rd pass and again increasing in 5th pass of the MAF. However, the shear stress components vary and are alternating between compressive and tensile states, with an unpredictable nature attributed to the rotation of the sample during MAF and die friction. Simulation results demonstrate an increasing trend of compressive residual stresses towards the centre with the progression of MAF passes but in 5th pass, tensile residual stresses develop between surface and inner region.