ABSTRACT

The stringent requirements of automotive and aerospace industries have prompted the design of newer materials with high strength to weight ratio, low coefficient of thermal expansion and high wear and corrosion resistance. Various automotive components are subjected to severe wear under close contact situations. It reflects to low power transmission, decrease the working efficiency, and components suffered from catastrophic failure during operation. Therefore, numerous efforts have been made to produce materials with excellent wear resistance characteristics. These efforts comprise the variety of alloying elements, different production techniques, and surface treatment. Aluminum-Silicon (Al–Si) alloys are one of the most promising materials for automotive and aerospace industries with acceptable mechanical properties including low density, excellent wear and corrosion resistance and low coefficient of thermal expansion. The properties such as tensile strength and corrosion resistance of the Al-Si alloys can further be enhanced by alloying with the small amount of copper and iron to extend its suitability for the particular application.

Wear resistance of the Al-Si alloys be governed by the Si wt.%, and it is higher for an alloy having greater Si amount. Therefore, the tribo-mechanical performance of the Al-Si alloy depends on the shape and size of the second phase particles and their distribution in the matrix. Thus, the Al-Si alloy exhibit superior tribo-mechanical properties having refined and uniformly dispersed second phase particles in soft Al matrix. While the presence of coarse and irregular-shaped second phase particles in the Al matrix deteriorates the tribo-mechanical performance of the Al-Si alloys and the components suffered from catastrophic failure during service.

Generally, different casting techniques were employed for producing of various Al-Si alloy components. During solidification, the cast morphology contains liquid segregation, coarse α-Al

dendrites and needle-shaped eutectic Si particles in the hypoeutectic composition of Al-Si alloys. Whereas coarse primary and needle-shaped eutectic Si particles were usually formed in the hypereutectic composition of Al-Si alloys. Such microstructural features deteriorate the mechanical and tribological properties of these alloys. Therefore, alteration of such microstructural features needed to improve the tribo-mechanical properties of the alloy. Mechanical and metallurgical properties of the Al-Si alloys depend on the shape and size of the silicon particles and their distribution in the Al matrix.

Casting techniques are unable to produce such components with adequate strength and toughness. Processing of Al-Si alloys through bulk metal forming techniques such as forging, extrusion, rolling, etc. have been found to be the most convenient way to improve the morphology of the cast Al-Si alloys and in turn, enhance the mechanical and tribological properties. The improvement in such properties is attributed to the refinement in microstructural features which leads to strong interface bonding between the second phase particles and Al matrix. Therefore, bulk processing is recommended for manufacturing of Al-Si alloys component with improved tribo-mechanical properties. The bulk processing has major advantages such as refined microstructural features, excellent mechanical properties and close tolerance of product.

However, bulk-forming techniques have many advantages, nevertheless, the processing of complex Al-Si alloys containing Cu and Fe metal through the metal forming route is very difficult due to the presence of hard and brittle silicon particles along with various complex intermetallic compounds. Such second phase particles are nucleate the cracks in Al matrix during deformation, which in turn fracture and surface defects in the final products and impairs its tribo-mechanical properties. Therefore, it is highly essential to modify such detrimental microstructural constituents into fine, and there uniform dispersion in the Al matrix which enhances the tribo-mechanical properties of the alloy and fulfill the industrial demands. Various processing parameters such as die set-ups, temperature, deformation ratio, lubrication, etc. during bulk-forming significantly affects the microstructural features and tribo-mechanical properties of the formed product. Therefore, systematic investigations are necessary to study the effect of the aforementioned processing parameter during bulk-forming of complex Al-Si alloy.

In view of the above facts, generation of cracks in the Al-Si alloys preform is a major concern during bulk processing and thus attracted the attention of researchers towards this issue to produce defect-free products. The present investigations have been undertaken to explore the feasibility of bulk processing of complex Al-Si alloys and also study the effect of various processing parameters on tribo-mechanical behavior. Therefore, the bulk processing was performed through open, impression, and converging die forging under different reduction rate, working temperature, and frictional conditions.

The thesis has the following seven (7) chapters.

Chapter-1: Introduction and Literature Review

This chapter comprises the brief introduction of the Al-Si alloy, its classification based on silicon contents. Mechanical, physical and tribological properties of Al-Si alloys are also discussed and its important applications. The relevant literature review based on the processing and characterization of the Al-Si alloys. It contains a concise survey on the different processing techniques, the effect of alloying elements, microstructural modification through different methods, and bulk-forming of the Al-Si alloys. The effect of processing temperature, different strengthening mechanisms and tribological behavior of Al-Si alloys under different working conditions are also discussed in this section.

Chapter-2: Experimental Work

This chapter presents the detailed experimental procedures to cast the alloys, to conduct the experiments using different die sets. The impression and converging die sets were machined from H11 die steel and heat treated. Three different Al-Si alloys were cast by varying the Si wt.% from 7.4, 11 and 18 along with 2.5 wt.% Cu and 0.6 wt.% Fe, and developed Al-18Si-2.5Cu-0.6Fe, Al-11Si-2.5Cu-0.6Fe, and Al-7.4Si-2.5Cu-0.6Fe alloys. Formation of different intermetallic compounds was identified by using x-ray diffraction (XRD) analysis and energy dispersive spectrum (EDS) techniques.

Deformation behavior of the complex Al-18Si-2.5Cu-0.6Fe, Al-11Si-2.5Cu-0.6Fe, and Al-7.4Si-2.5Cu-0.6Fe alloys was investigated during bulk processing. Different bulk processing techniques such as open, impression and converging die forging was performed at room and elevated working temperatures of 300, 400 and 500°C under different lubricating conditions. The effect of various processing parameters such as working temperature, aspect/reduction ratio, and lubrication on microstructural features, mechanical properties, and wear behavior of the forged alloy. The microstructural features of the as-cast and forged Al-Si alloys were evaluated from optical microscopy and scanning electron microscopy (SEM). The tensile strength and hardness of the as-cast and forged alloys were measured from Instron Machine and Vickers Microhardness tester respectively. A pin-on-disc tribometer was used to assess the wear behavior of the as-cast and forged alloys under dry sliding conditions.

The deformation behavior and mechanical properties such as tensile strength, elongation, hardness etc. of any alloy depend on the microstructural features. The x-ray diffraction (XRD) and energy dispersive spectrum (EDS) analysis confirmed the formation of complex intermetallic compounds β-$Al_{4.5}FeSi$ and Al_2Cu during casting in all compositions of Al-Si alloy.

Chapter-3: Deformation behavior and Tribo-Mechanical Properties of the Complex Hypereutectic Al-18Si-2.5Cu-0.6Fe alloy during Forging

This chapter presents the deformation behavior of the complex hypoeutectic Al-18Si-2.5Cu-0.6Fe and its effect on the tribo-mechanical properties during bulk processing. The microstructural studies reveal that presence of coarse polyhedral primary Si and needle-shaped eutectic Si particles along with intermetallics in the complex hypereutectic Al-18Si-2.5Cu-0.6Fe alloy. Such coarse second phase particles and their non-uniform dispersion deteriorate the deformation behavior of the alloy and generate severe surface cracks during bulk processing through open die forging at room temperatures and 300°C, and also in impression die forging at room temperature. It may be attributed to initiations and propagation of cracks due to stress concentration between second phase particles and Al-matrix during bulk processing. However, bulk processing of the alloy through impression die as well as converging die produces the defect-free forged products at the elevated working temperatures of 300, 400, and 500°C. It may be attributed to the softening of the alloy at the elevated temperature which induced ductility during bulk processing. Bulk processing of the alloy at the elevated temperature leads to the microstructural refinement in both impression and converging die forging. It may be due to the fracture and fragmentation of the coarse Si and intermetallic particles, and their uniform dispersion in the Al matrix during the forging process. Such refinement in microstructural features enhanced the tensile strength, hardness and wear behavior of the forged alloy.

Chapter-4: Deformation behavior and Tribo-Mechanical Properties of the Complex Hypereutectic Al-11Si-2.5Cu-0.6Fe alloy during Forging

This chapter presents the deformation behavior of the complex eutectic Al-11Si-2.5Cu-0.6Fe and its effect on the tribo-mechanical properties during bulk processing. The microstructural studies of the as-cast complex eutectic Al-11Si-2.5Cu-0.6Fe alloy confirm the presence of the needle-shaped eutectic Si and few primary Si particles along with complex intermetallics randomly distributed in the α-Al matrix. Such coarse second phase particles generate stress concentration with α-Al matrix and initiate cracks which further propagates during bulk processing progressed through the open die forging at room temperatures and 300°C, and also in impression dies forging at room temperature. Thus, the severe cracks were formed on the surface of the forged preform. While the defect free products were obtained through impression and converging die forging of the alloy at the elevated working temperatures of 300, 400, and 500°C. Bulk processing of the alloy at 300, 400, and 500°C lead to the microstructural refinement, which in turns enhances the tribo-mechanical properties of the forged alloy.

Chapter-5: Deformation behavior and Tribo-Mechanical Properties of the Complex Hypereutectic Al-7.4Si-2.5Cu-0.6Fe alloy during Forging

This chapter presents the deformation behavior of the complex hypoeutectic Al-7.4Si-2.5Cu-0.6Fe and its effect on the tribo-mechanical properties during bulk processing. The metallographic examinations of the as-cast complex hypoeutectic Al-7.4Si-2.5Cu-0.6Fe alloy revealed the presence of the needle and plate-shaped eutectic Si particles along with complex intermetallic phases randomly dispersed in the α-Al matrix. During bulk processing of the alloy generates few microcracks during open die forging at room temperatures and 300°C. It may be due to the absence of the primary Si and low hardness of the alloy, thus the small microcracks were developed on the forged preform. The defect-free forged products were obtained during bulk processing of the alloy through impression die forging at room and elevated temperatures, and also in converging die forging. Microstructural refinement was observed in the forged samples which in turn improves the tribo-mechanical properties of the alloy.

Chapter-6: Comparative Studies of the Bulk Processed Al-Si Alloys

This chapter shows the comparative study of the forged complex Al-Si alloys based on physical properties, deformation behavior, microstructural features, mechanical properties, and wear characteristics under dry sliding conditions.

Chapter-7: Conclusions and Scope for Future Work

The chapter depicts the important finding of the present research work and potential recommended work to carry out in the future.

List of Publications

1. **Khemraj**, Jha, A.K. and Ojha, S.N. (2017) 'Microstructural features induced during compression of Al-18Si-2.5Cu-0.6Fe alloy at elevated temperature', ***Int. J. Microstructure and Materials Properties***, Vol. 12, Nos. 5/6, pp.332–347. (https://doi.org/10.1504/IJMMP.2017.092162)
2. **Khemraj,** A.K. Jha, S.N. Ojha, (2018) 'Tribo-mechanical Behavior of Complex Hypereutectic Al-Si Alloy Compressed through a Converging Die at Elevated Temperatures' ***Materials Research Express***, 5, 076509. (https://doi.org/10.1088/2053-1591/aacc94)
3. **Khemraj,** Jha, A.K. and Ojha, S.N. (2019) 'Deformation and fracture characteristics of complex Al-Si alloy during high speed forging under different processing conditions', ***Int. J. Materials and Product Technology,*** Vol. 58, No. 1, pp.32–54. (https://doi: 10.1504/IJMPT.2019.096927)
4. **Khemraj**, A.K. Jha, S.N. Ojha, 'Deformation Behavior of A356, Al-11Si-2.5Cu-0.6Fe, and Al-18Si-2.5Cu-0.6Fe Alloys Forged under Different Processing Conditions',