# Effects of Processing Methods on Microstructure-Flow Property Relationships at Ambient and Elevated Temperatures in Binary Al-Si Alloys

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# 6
# Summary and Conclusions

This chapter includes a summary, concluding remarks, suggestions for future work, and closing comments based on the present work. The summary includes the objective of the current work and the experimental procedures, along with a brief description of the outcomes. In conclusion, the key results, along with the discussion of the detailed analyses of data, are presented. Also, the *suggestions for future work* emerge to represent relevant works, which can be of importance in furthering the insights reached here. Finally, the closing comments have been made to wind up the present thesis work.

## 6.1 SUMMARY

Binary Al-Si alloys of hypoeutectic (Al-2Si, Al-4Si, Al-8Si), eutectic (Al-12Si), and hypereutectic (Al-20Si, Al-30Si) compositions were produced by melting and casting of commercial-purity aluminium and silicon. These as-cast materials, and after their subsequent extrusion, severe plastic deformation by FSP and HPT methods, were used to investigate the microstructure and mechanical properties. The microstructures varied from dendritic coarse structures in as-cast to banded and equiaxed structures upon hot extrusion and ultrafine equiaxed grains upon FSP and HPT processing. These microstructures were quantified to find mutual relationships between composition, process, and microstructure. It was observed that the grain size decreases, and the Si particle size increases with the increase in silicon content. However, both grain size and particle size decrease with increasing severity of deformation, regardless of alloy composition.

Room temperature uniaxial tension, compression, and microhardness tests were performed to evaluate the mechanical properties of the differently processed Al-Si alloys. The yield strength and ultimate strength in tension and compression were noted to increase with increasing Si content up to eutectic composition, but decreased for higher Si-containing Al-Si alloys. Conversely, elongation was found to be higher in eutectic composition but decreased with increasing Si content. The maximum elongation was obtained for the extrusion Al-12Si alloy, and the maximum tensile strength for the FSP Al-12Si alloy. Hardness is noted to increase linearly with increasing Si content, irrespective of processing methods, and is found to be the maximum in HPT samples. The strength and grain size relationship given by Hall-Petch was also followed in some cases of as-cast, extrusion, and FSP Al-Si alloys.

The high-temperature tensile tests were conducted by using constant initial strain rate and differential strain rate-differential temperature test techniques. Also, a coupled DSR-CSR test technique was used to get both parameters of the constitutive relationship ($m$, $Q$) and the combined effects of DSR and CSR tests on the final elongation. The $m$ and $Q$ values were determined from the data obtained in DSR tests for all the Al-Si alloys. Based on the $m$ and $Q$ values, it was found that in as-cast and extrusion Al-Si alloys, dislocation climb creep is the active deformation mechanism, whereas FSP-processed Al-Si alloys exhibit a superplastic deformation mechanism, which consists of grain boundary sliding and diffusional process. The maximum elongation for superplasticity was noted to be 341% for the FSP eutectic Al-12Si alloy.

Superplastic elongations of 300% and 191% were also obtained in other hard-to-work FSP Al-20Si and Al-30Si alloys. The interrelationships between the mechanical properties at room temperature and high temperature, between grain size and particle size, and between the microstructure and mechanical properties were suggested to exist irrespective of alloy composition, processing methods, and test conditions.

## 6.2 CONCLUSIONS AND REMARKS

- Coarse microstructures of as-cast Al-Si alloys (115μm maximum) were modified into equiaxed fine grains of ~5-8 μm after hot extrusion and ultra-fine grains of ~1-2 μm upon severe plastic deformation. The coarsening occurred with increasing extrusion temperature. The degree of refinement increased with an increasing number of FSP passes and HPT turns. Also, the redistribution of phases after SPD makes the microstructures more homogenous. It can be understood by observing the matrix and particle size distribution plots. Overall, it can be stated that the HPT process is the best method for microstructural refinement.

- The hardness of Al-Si alloys increases linearly with increasing Si content and shows an irregular trend with the processing methods. HPT samples exhibited the highest hardness because of the ultrafine grains and fine silicon distribution in the matrix. Among as-cast, extrusion, and FSP, tensile elongation shown by extrusion was the maximum, whereas its hardness was the minimum.

- The nature of stress-strain curves can be expressed by Hollomon-type relationships. The associated work hardening follows stage III behaviour in tension and stage III and IV behaviour during compressive deformation. The stress-strain curves in tension and compression exhibit asymmetry, which increases with increasing Si content. However, the asymmetric nature decreased after the hot extrusion processing of the Al-Si alloys.

- The Hall-Petch type relationship is found to follow in hardness, tension, and compression tests to show the effect of grain size on the variation in strength. As-cast material appears to be more sensitive to grain size with maximum $k_{HP}$ compared to that obtained from other processing methods.

- At high temperatures, stress-strain curves exhibit flow hardening, pseudo-steady state, and prolonged flow softening with concurrent grain refinement and phase redistribution of α-Al and Si particles and cavitation to varying degrees depending on the alloy composition, processing methods, and test conditions. These changes in properties are found to be mutually related not only at elevated temperatures but also with their room temperature properties. The peak stress and the stress at the onset of plastic strain follow a linear relationship, whereas the strength-ductility plot shows the standard banana shape. Also, the variation in room temperature hardness as a function of elongation at elevated temperature follows the standard banana-type shape, whereas the same hardness plotted as a function of grain size evolved follows the Hall-Petch type relationship in line with the initial samples.

- There appeared concurrent grain growth and cavitation during high-temperature deformation of fine-grained Al-Si alloys. The FSP-processed samples exhibited both grain growth and cavitation to be the maximum. The growth of α-Al matrix ($d_a$) and Si particle ($d_p$) sizes was determined to be 430-530% and 160-280%, respectively; the Zener drag type plot ($d_a/d_p$ vs. $f_p$) was followed amongst the data from different alloy compositions.

- Overall, the strain rate sensitivity index ($m$) varies from 0.04 to 0.4, and the activation energy for deformation ($Q$) is obtained in the range of 79-572kJ/mol for the temperature range of 450K-840K and strain rate of $10^{-4}$-$10^{-2}s^{-1}$ in Al-2Si to Al-30Si alloys for as-cast (CS), extrusion (ES) and FSP (FS) processed materials. It was apparent that the magnitude of $m$ increased in the order of $m_{CS}<m_{ES}<m_{FS}$; the maximum values of the parameters of the constitutive relationship $m$ and $Q$ were noted in the FSP-processed eutectic Al-12Si alloy.

- The FSP processed hypo to hypereutectic Al-Si alloys exhibit superplasticity with the maximum elongation of 341% for eutectic Al-12Si at 840K and $10^{-4}s^{-1}$ with $m$=0.4. The mechanism for high-temperature deformation changed from dislocation climb-controlled (non-superplastic, $m\approx$0.2-0.25) to grain boundary sliding and its accommodation by diffusional process (superplastic, $m\geq$0.3) in the FSP processed material. In as-cast and extruded materials, deformation occurs by a dislocation climb-controlled mechanism at higher temperatures and lower strain rates, whereas it changes to power law breakdown at lower temperatures and higher strain rates.

## 6.3 SUGGESTIONS FOR FUTURE WORK

The present work can be expanded by exploring the in-depth characterization techniques and by using some sophisticated instruments to enhance the understanding of the electronic and thermal properties of Al-Si alloys. The following points can be considered as future suggestions for the present work.

I. In-depth characterization by using TEM and EBSD can be done to better understand the deformation behaviour of two-phase Al-Si alloys.

II. High-temperature tests can be planned for HPT samples to check the possibility of enhanced superplasticity.

III. Thermal and electrical properties can also be measured, which will broaden the application of Al-Si alloys in the electronics industry.

IV. The integration of the effects on structure and properties of all the materials undergoing different processing can enhance the process-structure-property and strength-ductility synergy. This could then also be extended to the combination of different processing methods for further enhancement of properties.

V. The machine learning approach can be utilized to improve the composition-process-structure-property-performance relationship.

## 6.4 CLOSING COMMENTS

Al-Si alloys constitute basic light metals, which have undergone several modifications in composition and processing, but not much has been done in spite of several attractive developments in mechanical working. Therefore, this work started with the motivation of the importance of the Al-Si alloys and the research gap on the same. This was pushed to get some valuable results that covered the entire spectrum of Al-Si compositions, processing methods, and mechanical properties over the range of test conditions. The obtained values of parameters of the constitutive relationship distinguished the deformation mechanisms for different compositions, different processing methods, and temperature ranges. Interestingly, it was possible to get superplasticity in hard-to-work hypereutectic Al-Si alloys, which can enable metal forming of this alloy for different simple-to-intricate components for a range of industrial

applications. Thus, the present work opens up the possibility of acknowledging the importance of established materials but yet to make attempts to compete with other emerging materials by making use of new technological evolution at any stage from raw material to final product form.

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