Effect of constituent-particles distribution on mechanical behavior of an AlMgSi alloy

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Abstract. In the present work, the effect of constituent particles distribution on mechanical behavior of a high strength AlMgSi alloy is investigated. The study consists of the tensile and fatigue testing of the material in longitudinal and transverse directions. Monotonic tensile properties, in both the directions showed virtually identical yield and tensile strengths. However, higher values of elongation and reduction in area were observed in the longitudinal direction. SN curves produced after fatigue testing displayed a shorter fatigue life in transverse direction as compared to the longitudinal direction. Microstructural analysis exposed that the material had clusters of constituent particles. Post fracture analysis of tensile and fatigue samples, in SEM, revealed that the topographical features change with the sample orientation. The present study revealed that the distribution of constituent particles in longitudinal and transverse directions has a pronounced effect on the tensile and fatigue behavior of the alloy and also induce anisotropy in the material.

1. Introduction
Generally mechanical processing in the form of rolling, forging, drawing etc. is included in the manufacturing route of the wrought components. These processes are thought to be essential to attain the ultimate mechanical properties of such components. During these processes the physical dimensions of the material change and the effect can be seen on the microstructural scale. Grains as well as other constituent features undergo substantial changes which significantly influence the mechanical properties and often create anisotropy in the material. The anisotropy produced in the material results in dissimilar properties along different orientations of the product and is undesirable in several applications. Subsequent thermal processes are used to minimize the directionality effect and achieve an isotropic material. The microstructural features thus developed in the final product play a pivotal role to establish the mechanical properties.

The response of the microstructural features against these mechanical processes depends upon their mechanical behavior at the processing conditions. Metal in the form of grains, easily deform at high temperature and elongate in the allowable direction. Constituent particles in the material behave differently under loading conditions. For example, sulphides normally present in steels, show a ductile behavior and deform under the processing conditions. However, oxides in general exhibit a brittle behavior and fracture during processing. Debonding easily occurs where these particles show weak adherence with the matrix and deformation behavior of the material considerably changes. Chemistry of these constituent particles, their density, size, distribution, morphology and the adherence with the matrix are main controlling factors which ultimately affect the mechanical behavior of the material.

Aluminum alloys are of vital importance for many structural applications in automotive, marine and aircraft industries [1]. The principal design features of these alloy systems are their high strength with low...
density along with high corrosion resistance. In aluminum alloys, constituent particles are formed during the cooling process when some of the alloying elements solidify more rapidly than the aluminum. The mechanical properties of aluminum alloys are greatly influenced by the presence of these particles.

The AlMgSi alloys are frequently used due to relatively high strength, good corrosion resistance and high toughness in addition to their good formability and weldability [2-3]. In AlMgSi alloys ultimate mechanical properties are achieved in T6 temper. This includes solution heat treatment at 530 °C for adequate time to allow thorough heating and then water quenching. Aging precipitation heat treatment is done at 175 °C for 8 hours followed by air cooling [4].

Mechanical testing is frequently conducted to acquire the material’s data required for modeling the mechanical systems. The monotonic tensile test is a simple and versatile test to evolve most of the mechanical properties under tension [5]. Fatigue testing is mandatory to explore the behavior of the material under cyclic loading.

Metal fatigue is significantly influenced by microstructure. Investigations of the aluminum alloys under fatigue loading have been extensively done [6-9] and the constituent particles are found to play an important role in the fatigue life of these alloys. Many researchers have made experimental observations of the types of features that become sites for nucleation of fatigue cracks in aluminum alloys. Generally, it was observed that the cracks were formed at debonded or broken constituent particle clusters or at particles that cracked during rolling. Minimizing discontinuities including the constituent particles in aluminum alloys is a key to good fatigue resistance. In a study on AlCuMg bars, it was observed that reducing the density of constituent particles significantly enhanced the fatigue resistance of the alloy [10]. The objective of the research work is to determine the effect of orientation on tensile and fatigue performance of high strength AlMg1SiCu alloy in T6 condition. The study consists of the tensile and fatigue testing of the samples taken from transverse (TR) and longitudinal (LD) directions. The results obtained from the monotonic tensile test of round samples and SN curves from the fatigue testing of middle tension (MT) samples are presented. Prior to mechanical testing, the microstructural analysis of the material was conducted with the help of optical and scanning electron microscopes. After the tests, the topographical features of the fractured surfaces were examined in Scanning Electron Microscope (SEM).

2. Experimental procedure

2.1. Material characterization

The material used for this study was AlMg1SiCu aluminum alloy in T6 condition. The chemical composition of the material was determined using Energy Dispersive spectrometer (EDS) in SEM. The microstructural features in two orientations were investigated with the help of optical microscope and SEM.

2.1.1. Chemical composition

The chemical composition of the material is given in table 1. The material confirms the specifications of aluminum alloy AlMg1SiCu. The major constituents of the alloy are Al, Mg and Si.

| Material | Mg  | Si  | Fe  | Cu  | Cr  | Mn  | Al  |
|----------|-----|-----|-----|-----|-----|-----|-----|
| Rod      | 0.94| 0.64| 0.20| 0.19| 0.10| 0.06| Bal.|
2.1.2. **Microstructural analysis**
Metallographic sections were prepared using standard procedures and optical and scanning electron microscopes were used to examine the microstructural features of the alloy. Samples were studied in polished as well as etched conditions, in two orientations. Etching was done in 3% HF solution to reveal the grain size and their orientation. EDS analysis of the constituent particles was conducted in SEM.

2.2. **Monotonic tensile testing**

2.2.1 **Test sample**
Samples were taken in LD and TR directions as shown in figure 1. Round tensile samples were machined with final dimensions as given in figure 2. The gauge section of the samples was polished using aluminum oxide powder.

![Figure 1. Orientations of tensile (T) and fatigue (F) specimens used in this study.](image)

![Figure 2. Dimensions of the tensile sample (in mm).](image)

2.2.2 **Testing procedure**
Monotonic tensile tests were conducted to obtain stress-strain curves in two orientations. Tests were conducted at a strain rate of $3.3 \times 10^{-5}$ per second. An extensometer of 25 mm gauge length was attached to the sample in the gauge section. The load and elongation data was recorded and subsequently stress strain curves were obtained. Five samples were tested for both orientations.

2.3. **Fatigue testing**

2.3.1 **Sample preparation**
Fatigue testing was performed on middle tension (MT) specimens prepared in two orientations. Samples were cut from the extruded cylinder and machined to final dimensions according to the standard ASTM E 647 [11]. Samples were subjected to mechanical grinding and subsequently fine polishing with 1 μm alumina powder to minimize the surface roughness effects. Dimensions of the sample in TR orientation are given in figure 3. The length, width and thickness of LD sample were 80, 20 and 2.5 mm, respectively.

![Figure 3. Dimensions of the MT sample (in mm) - TR direction](image)
achieved. Crack length was measured with the help of traveling microscope at a magnification of 100x. Tests were interrupted for short times to measure the crack length. During testing, the number of cycles and crack extension data were recorded until failure. Testing was conducted in air at 20 °C and approximately 50% relative humidity.

2.4. Fractography
The macroscopic and microscopic examination of the failed samples was conducted after mechanical testing to understand the effect of orientation on fracture mechanism. The fractured surfaces of the specimens were cut, cleaned in acetone and examined in SEM. The images of the important features were recorded during examination.

3. Results and discussion
3.1. Microstructural features
The optical microstructure of the alloy is shown in figure 4(a,b), in two orientations. The etched microstructure revealed that it consisted of recrystallized grains. It seems that the grains elongated during processing and recrystallize into fine almost equiaxed grains during subsequent heat treatment. The morphology and the alignment of the constituent particles were not affected by heat treatment process.

Figure 4(a, b). Optical micrographs revealing the microstructure of the alloy in a) LD and b) TR direction

Figure 5a shows the SEM micrograph of the polished sample revealing constituent particles in the LD direction. Further examination after etching exposed that the constituent particles were present preferably along the grain boundaries. The particles can be seen aligned along the extrusion direction. Inspection at high magnification revealed that clusters of particles were present at these locations; see figure 5b.

Figure 5(a, b). SEM micrographs of the alloy showing the constituent particles in longitudinal direction a) low mag. b) high mag. (clusters of particles)

It seems that these particles were formed during solidification and fractured in fragments and aligned along the direction of working. EDs analysis showed that these particles were rich in Al, Fe, Si, Cr and Mn. The other type of particles found in the material was rich in Al, Mg and Si.
3.2. Monotonic tensile test

The stress-strain diagrams obtained after tensile testing in two orientations are presented in figure 6. These graphs indicate that the behavior of the material, under tensile loading, remains essentially same up to the point of yield strength. This shows that the response of grain structure and the constituent particles is similar in both the samples up to this point. However, after this point, difference of the two curves is visible. A smaller strain value up to the point of failure in transverse direction indicates that the distribution of constituent particles in this orientation restricted the material to deform much before fracture.

The results obtained from the tensile tests of the alloy in two orientations are given in Table 2. The table also provides the hardness measured along two sections. The analysis of the above results shows that the yield strength and ultimate tensile strength of the material in the two orientations were not different. However, the difference in the deformation behavior was significant. In LD direction the material has higher ductility represented by the elongation and reduction in area. These properties indicate that the recrystallized grain structure has eliminated the effect of texture on the yield and tensile strengths of the material. However, the texture produced by the clusters of the constituent particles was not eliminated by subsequent heat treatment processes and that reduced the elongation and reduction of area in the transverse direction.

| Table 2. Nominal tensile properties of the alloy |
|-----------------------------------------------|
| Properties | Orientation |
|     | Longitudinal | Transverse |
| 0.2 % Yield strength, MPa | 324 | 322 |
| Ultimate tensile strength, MPa | 354 | 353 |
| Elongation, % | 16 | 9 |
| Reduction in area, % | 50 | 24 |
| Elastic modulus, GPa | 71 | 71 |
| Hardness, HV | 115 | 115 |

3.3. Fatigue test

3.3.1 Fatigue life analysis

The graphs of the stress range vs. the number of cycles to failure (SN curves) for TR and LD orientations are given in figure 7. Fatigue life increases as the stress range decreases for both the orientations. SN curves revealed a shorter fatigue life of the samples prepared in TR orientation; a possible explanation of which is the distribution of the constituent particles. Clusters of aligned particles in TR orientation were present in the direction perpendicular to the loading axis and more favorably oriented to assist the crack growth process. The difference in number of cycles to failure in two orientations at four stress levels is
given on the graph. It can be seen that the difference is increasing with lowering stress level. This indicates that the microstructural variation in the two orientations is more effective at low stress levels.

Figure 7. Stress range vs the number of cycles to failure for the two orientations

Figure 8. Plots of the crack length versus the number of cycles to failure for two orientations

3.3. Crack extension

Figure 8 shows the crack length versus the number of cycles to failure for two orientations at three stress levels. The data covers the range from start of the crack at the notch tip up to the specimen failure. In both orientations, the number of cycles to start the crack from the notch and the maximum value of the crack length increase with the decrease in the stress level. Comparing the curves for two orientations, at the same stress level, it is evident that in TR orientation the crack started earlier. Start of the crack at comparably low number of cycles indicates that the distribution of the constituent particles is favorable in TR orientation to nucleate the crack from the notch tip.

3.4. Post-fracture analysis

3.4.1 Tensile samples

SEM fractographs of the tensile samples in two orientations are shown in figure 9. In LD sample necking is visible indicating higher ductility in this orientation. The fracture is at an angle of about 45°. Figure 10 shows SEM fractographs at high magnification of the samples shown in figure 9. The micrographs in both the orientations showed typical dimple fracture indicating deformation before failure. The presence of constituent particles in the dimples showed that these were the crack initiation sites. Clusters of particles as were observed in the metallographic sections were present in the TR orientation.

3.4.2 Fatigue samples

The fracture surfaces of the fatigue samples tested at maximum stress of 20% yield strength in two orientations are shown in figure 11. The corresponding numbers of cycles to failure for LD and TR samples were 63672 and 28653, respectively. Starter notch in both the samples is marked on the micrographs. In LD sample, only the crack growth region is visible and the overload region is out of the micrograph. In TR sample, shown in figure 11b, both the crack growth and the overload failure
Figure 9(a, b). SEM micrographs of the fractured tensile samples a)LD b)TR orientation regions are shown. The macro appearance of the two fractured surfaces is markedly different and represents the corresponding microstructures observed during metallography. Figure 12 shows the higher magnification images of the fatigue crack growth region shown in figure 11. These microscopic views show fatigue facets created by propagation of the fatigue crack. Cluster of fragmented constituent particles can be seen in the center of figure 12b. The mode of failure locally changed due to the presence of these particles. Inspection of the fractured surfaces at higher magnification shows striations on the fatigue facets. This indicates that the general mechanism of crack growth was the formation of striations. In the final rapid fracture ductile dimples were observed in both the samples.

Figure 10(a, b). SEM micrographs of the fractured tensile samples at high mag. a)LD b)TR orientation

Figure 11(a, b).SEM micrographs of the fatigue fracture samples tested at maximum stress of 20 %YS a) LD b)TR orientation
4. Conclusions

Following conclusions can be drawn on the basis of the present study;

- The material was composed of recrystallized grains. Clusters of constituent particles were present aligned along the direction of processing.
- Monotonic tensile properties of the material in two orientations revealed that the yield and tensile strengths were virtually identical. However, higher values of elongation and reduction in area were observed in the longitudinal direction.
- SN curves of the samples in two orientations showed a shorter fatigue life in TR direction. The difference was more visible at low stress levels.
- Post fracture analysis revealed that the topographical features change with the sample orientation. Tensile samples showed typical dimpled failure where constituent particles were the main crack nucleating sites.
- The present study revealed that the distribution of constituent particles after processing has a pronounced effect on the tensile and fatigue performance of the alloy and induced anisotropy in the material.

5. References

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