Effect of retrogression and re-aging on mechanical & wear properties of LM-25 aluminium alloy

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Abstract. The effect of retrogression and re-aging on the mechanical and wear properties of LM 25 were studied. The raw material ingot was casted into cylindrical rods. The samples were solutionized at 530 °C for 2 hours and then artificially aged at 165 °C for 12 hours. The samples were heat treated using retrogression process at temperatures 200 °C, 225 °C, 250 °C, and 275 °C and re-aged at 165 °C for 12 h. The samples were tested for its hardness and tensile strength and found that the 200°C retrogressed and re-aged sample (HT1) was having high hardness (125 HV) and the tensile strength was recorded as highest (182 N/mm²) when compared to other samples. Izod impact test was conducted for all the samples and it remains same for all the samples. Dry sliding wear test results shows that HT1 sample was having least wear rate when compared to other samples. Microstructure of HT1 sample reveals that the silicon precipitates of sleek and finer grain structure, which improves the hardness and tensile strength.

Keywords: LM 25, Retrogression, Ageing, Wear rate, hardness

1. Introduction

Lightweight aluminium alloy properties improved by heat treatment techniques are now becoming the choice of automotive manufacturers. Aluminium was widely used in many of the automotive applications such as body structure, gear box casing, pistons, cylinder heads, intake manifolds and wheels [1]. Aluminium alloys are broadly classified into wrought and cast categories. In the cast aluminium alloy LM 25 is widely used in automotive transmission cases and aircraft structures. LM 25 mechanical and tribological properties can be improved by the artificial ageing process and also the base alloy properties can be further improved by reinforcing with AlB₃[2]. In order to improve the cast A 356 aluminium alloy it is reinforced with SiC particles and found that the wear resistance is improved [3]. In general Al-Mg-Si alloys are heat treatable and its mechanical properties can be improved by artificial ageing process. During this process magnesium joined together with silicon and forms a precipitate called magnesium silicide (Mg₂Si). These formations of fine grain Mg₂Si precipitates act as a primary hardening phase and decides the strength of the alloy [4]. In one of the study the effect of size, morphology and volume fraction of the hardening precipitate was analysed for the 6061-T6 welded joints. The effect of heat input on the hardness of welded joints were studied [5]. In another study LM 25 was solutionized at 495 °C for a period of 8 hours then the samples were oil quenched at 35 °C and finally artificially aged at 175°C for a period of 6 hours and found that the hardness and tensile strength was improved [6]. LM 25 was reinforced with steel wire using stir casting technique and found that the tensile and compression strength was improved [7].
In one of the research, high strength weldable aluminium alloy-2195 was processed with retrogression and re-ageing (RRA) heat treatment technique to study the effect on the mechanical properties. In RRA process the samples are artificially aged and heat treated at high temperatures below solvus line for short duration and then reaged for long time at a low temperature. The effects of RRA on the mechanical properties of Al 2195 were studied [8]. In another study Al 7075 were heat treated with RRA process and found that the hardness is increased. Also it was noted that the RRA temperature influences the mechanical properties [9]. RRA heat treatment was carried out on Al 7075 and found that the corrosion property is improved [10].

In this study, the effect of RRA heat treatment on mechanical and corrosion properties of aluminium LM 25 alloy were investigated. The objective of the study was to determine the optimal combination of retrogression temperature to maximize mechanical and corrosion properties of aluminium LM 25 alloy.

2. Materials and methods

The base raw material LM 25 was tested for its elemental composition and is reported in the Table 1.

Table 1. Elemental composition of LM 25 aluminium alloy.

| Element | Cu   | Mg   | Si  | Fe  | Mn  | Ni  | Zn  | Pb  | Sn  | Ti  | Al  | Others |
|---------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
| Percentage | 0.2 | 0.2- | 6.5 | 0.5 | 0.3 | 0.1 | 0.1 | 0.05 | 0.2 | 98.1 | 0.05    |

The base raw material LM 25 ingot was melted and casted into twenty cylindrical rods of each 30 mm diameter and 300 mm length. The resulting twenty cylindrical rods were divided into five sets (HT1, HT2, HT3, HT4, UT) of four samples each, here ‘HT’ is Heat treated and ‘UT’ is Untreated.

2.1. Retrogression and re-ageing

The heat treatment process for the four sets (HT1, HT2, HT3, HT4) were carried out. Each set consists of four cylindrical rods. All the four sets were solutioniz ed at a temperature of 530°C for 2 hours and then waterquenched rapidly. After solutionization, the four sets were artificially aged at a temperature of 165°C for a period of 12 hours. After the artificial aging process, the four sets were heat treated using the retrogression process for a period of 2 hours with the first set (HT1) at a temperature of 200°C, the second set (HT2) at a temperature of 225°C, the third set (HT3) at a temperature of 250°C and the fourth set (HT4) at a temperature of 275°C respectively. Following the retrogression process, all the four sets were artificially re-aged at a temperature of 165°C for 12 hours. The whole heat treatment process was carried out in a Nitrogen gas atmosphere so as to avoid oxidation of the alloy. The furnace’s raising time and settling time also were considered. The process of retrogression heat treatment with respect to temperature and time is illustrated in Figure 1.

![Figure 1. Heat treatment temperature vs time curve.](image-url)
2.2. Tensile testing

The samples were tested for its tensile strength using Tinius Universal Testing Machine (UTM) having a loading capacity of 2500 Kg. Three specimens from five sets (HT1, HT2, HT3, HT4, UT) were cut and machined to specimens having gauge length of 36 mm and diameter of 9 mm. The testing was carried out according to standard ASTM E8-16a. The tensile specimen’s nomenclatures are shown in the Figure 2. The corresponding dimensions of the tensile specimen were presented in the Table 2. The ultimate tensile strength of each sample was noted.

Table 2. Dimensions of tensile test specimen

| Specimen specifications |
|-------------------------|
| Total length, L         |
|                        | 100 mm                  |
| Gauge length, G         |
|                        | 36 mm                   |
| Grip portion diameter, D|
|                        | 11 mm                   |
| Gauge diameter, d       |
|                        | 9 mm                    |
| Chamfer, C              |
|                        | 1 mm x 45 °             |

2.3. Microhardness

The hardness measurement was carried out on one specimen from each set using Mitutoyo Vickers hardness testing machine (MVH-H11) with square pyramid diamond indenter. One specimen from each set was machined to the ASTM E384 specifications, Ø10 mm; 10 mm height. The microhardness is measured with load of 100 gf for a dwell time of 15 s. Minimum of five points were used to get the average microhardness.

2.4. Dry sliding wear tests

Pin-on-disc equipment is used to conduct the dry sliding wear tests. The wear test was conducted with the varying load of 10, 20 and 30 N and with sliding velocity asconstant at 2 ms⁻¹for all the five set of samples. Then another wear test was conducted with the load as constant at 20 N and varying the sliding velocity as 1 ms⁻¹, 2 ms⁻¹and 3 ms⁻¹. During both the tests the sliding distance was kept constant at 1200 m. The speed of the rotating disc was 191, 382, and 573 rpm. ASTM G99-95a standard was followed. The pin (Ø10 mm x 55 mm length) is held stationary against the counter-face of a 50 mm diameter rotating disc. Samples were cleaned before and after the test. Weights of the samples were measured. Wear rate is determined as the ratio of weight loss divided by the product of the density and sliding distance.

2.5. Impact test

Izod impact testing was performed at 31.1 °C with a notched specimen with specifications of IS:1598-1997 standard. The specimen is a square prism of dimension 77 mm x 10 mm x 10 mm with a V-notch of 2 mm depth at 22 mm from one side of the specimen. Three specimens each from five batches were tested and the average impact strength of each batch is obtained. The izod impact test specimen nomenclatures are shown in the Figure 3. The corresponding dimensions of the izod impact specimen is listed in the Table 3.
Table 3. Dimensions of impact test specimen

| Specimen specifications       |          |
|------------------------------|----------|
| Length, L                    | 75 mm    |
| Width, W                     | 10 mm    |
| Height, H                    | 10 mm    |
| V-Notch depth, D             | 2 mm     |
| V-Notch angle, A             | 45°      |
| Notch distance, (N)          | 28 mm    |
| Striking distance of V-Notch| 22 mm    |

Figure 3. Izod Impact test specimen dimensions.

2.6. Microstructural study

The specimens were polished and etched with Keller’s reagent. Microstructure images were captured using optical microscope at 100X, 200X and 500X magnifications using a camera linked to the computer system.

3. Result and discussions

After heat treatment of samples of four batches (HT1, HT2, HT3, HT4), specimens were separately tested for the tensile strength, microhardness, wear resistance, impact strength and the corrosion properties. The results in various tests were discussed below.

3.1. Microhardness

Hardness measurement was carried out on LM 25 aluminium alloy at a load of 100 gf for 15 s at room temperature using Mitutoyo Vickers hardness testing machine. Minimum of five points are used to get the average value of microhardness of each set. The maximum hardness is observed in HT1 samples, retrogressed at 200 °C, with average value of 125 HV. Microhardness of all samples was reported in Table 4.

| Averaged observed readings | Sets |
|----------------------------|------|
|                            | UT   | HT1  | HT2  | HT3  | HT4  |
| Microhardness (HV)         | 87   | 125  | 105  | 93   | 62   |

3.2. Tensile test

The stress-strain diagrams obtained for the five sets of samples-UT, HT1, HT2, HT3 and HT4, each tested at same elongation speed, are plotted in Figure 4, 5, 6, 7 and 8 respectively. The average values of tensile strength (N/mm²), maximum load (kN), final gauge length (mm) and percentage elongations (%), of each set are given in Table 5. As a result of RRA treatment the strength increases initially and decreases gradually with the increase in retrogression temperature. It is obvious that HT1 samples, retrogressed at 200 °C, has the highest strength of 182 N/mm² and highest elongation about 9.04 % compared to other sets (UT, HT2, HT3 and HT4) which can be inferred from Table 5.
Figure 4. Stress vs Strain graph of UT

Figure 5. Stress vs Strain graph of HT1

Figure 6. Stress vs Strain graph of HT2

Figure 7. Stress vs Strain graph of HT3

Figure 8. Stress vs Strain graph of HT4

Table 5. Tensile test average values

| Averaged Observed readings | UT      | HT1      | HT2      | HT3      | HT4      |
|---------------------------|---------|----------|----------|----------|----------|
| Tensile strength (N/mm²)  | 123.4   | 182      | 169.53   | 151.2    | 109.63   |
| Load at peak (kN)         | 7.849   | 11.579   | 10.784   | 9.621    | 6.975    |
| Final gauge length (mm)   | 38.83   | 39.25    | 39.01    | 38.9     | 38.84    |
| Percentage elongation (%) | 7.86    | 9.04     | 8.37     | 8.07     | 7.90     |

3.3. Impact test

Izod pendulum tests resulted in a single value for the energy required to break a specimen. The results of Izod impact test are presented in Table 6. These results disclose that there were no effect of retrogression and re-aging on impact strength of LM 25.
Table 6. Izod impact test values

| Averaged observed readings | UT | HT1 | HT2 | HT3 | HT4 |
|----------------------------|----|-----|-----|-----|-----|
| Izod impact energy (J)     | 2  | 2   | 2   | 2   | 2   |

3.4. Microstructure study

The microstructure images of all the five sets were taken using metallurgical microscope. The structure and distribution of silicon precipitates in the eutectic phase were observed in the microstructures at different magnification factor (100X, 200X and 500X). The micrographic image of UT sample is shown in Figure 9. The microstructure of UT depicts the silicon precipitates in the aluminium matrix with coarse grain structure, more dispersed and unevenly distributed. The microstructure of HT1 specimens shown in Figure 10 shows the silicon precipitates were sleek with fine grain structure and were evenly distributed throughout the aluminium matrix. The microstructure images of HT2, HT3 and HT4 shown in Figure 11, 12 and 13 depicts that the silicon precipitates were dispersed more as the retrogression temperatures increased. The change in orientation of silicon precipitates in specimens retrogressed at 200 °C enhances the performance of LM 25 aluminium alloy. The higher dispersion of the silicon precipitates at higher retrogression temperatures (225°C, 250°C, 275 °C) degrades the overall performance of LM 25 aluminium alloy.

Figure 9. Microstructure of UT specimen at 100X, 200X and 500X.

Figure 10. Microstructure of HT1 specimen at 100X, 200X and 500X.

Figure 11. Microstructure of HT2 specimen at 100X, 200X and 500X.
3.5. Dry sliding wear test

Wear rate of five sets of samples (UT, HT1, HT2, HT3, HT4) were investigated with the constant sliding velocity of 2 m/s and with a varying load of 10, 20 and 30 N. The wear test results were presented in Table 7. The wear rate of UT, HT1, HT2, HT3 and HT4 specimens are maximum at 30 N and are 1.68 m³/m, 1.55 m³/m, 1.77 m³/m, 2.09 m³/m, 2.22 m³/m respectively. The wear rates is minimum with the load of 10 N and are 0.44 m³/m, 0.38 m³/m, 0.57 m³/m, 0.67 m³/m and 0.79 m³/m of UT, HT1, HT2, HT3 and HT4 specimens respectively. The effect of load on the wear rate of the specimen for constant sliding velocity of 2 m/s is plotted in Figure 14.

Similarly, wear rate of five sets of samples (UT, HT1, HT2, HT3, HT4) were investigated with the constant load of 20 N and with a varying sliding velocity of 1, 2 and 3 m/s. The wear test results were presented in Table 8. It can be inferred from the wear data that with an increase in sliding velocity the wear rate reduces. The effect of sliding velocity on the wear rate of the specimen for the constant load of 20 N is plotted in Figure 15.

Table 7. Wear rate at constant velocity. (2 ms⁻¹)

| Sl.no. | Load (N) | Time (min) | UT (m³/m) | HT1 (m³/m) | HT2 (m³/m) | HT3 (m³/m) | HT4 (m³/m) |
|--------|----------|------------|-----------|------------|------------|------------|------------|
| 1      | 10       | 10         | 0.44      | 0.38       | 0.57       | 0.67       | 0.79       |
| 2      | 20       | 10         | 1.24      | 1.17       | 1.30       | 1.43       | 1.49       |
| 3      | 30       | 10         | 1.68      | 1.55       | 1.77       | 2.09       | 2.22       |

Table 8. Wear rate at constant load, 20 N

| Sl.no. | Velocity (ms⁻¹) | Time (min) | UT (m³/m) | HT1 (m³/m) | HT2 (m³/m) | HT3 (m³/m) | HT4 (m³/m) |
|--------|-----------------|------------|-----------|------------|------------|------------|------------|
| 1      | 1               | 10         | 1.46      | 1.14       | 1.27       | 1.20       | 1.52       |
| 2      | 2               | 10         | 1.36      | 1.11       | 1.24       | 1.17       | 1.43       |
| 3      | 3               | 10         | 1.27      | 0.97       | 1.10       | 1.06       | 1.35       |
Figure 14. Load vs Wear rate at constant velocity. Figure 15. Sliding velocity vs Wear rate at constant load.

It can be inferred from Figure 14 that the wear rate is increasing when the applied load is increasing. The rotating EN 31 steel disc is harder than the specimen, so during the initial wear condition, the hard asperities of disc creating the fragmentation of the soft pin surface. When the applied load increases the contact pressure and friction increases on the wear test samples. This leads to increase in temperature and softening of the aluminium alloy which causes more metal removal [11, 12].

It can be inferred from Figure 15 that the wear rate decreases as sliding velocity increases. Due to increase in sliding velocity, the frictional force between the pin and the steel disc increases which lead to increase in temperature. This increase in temperature leads to softening of the pin and forms an oxide layer over the tip. This oxide layer helps in sliding over the steel disc very freely which resulted in less wear rate [13, 14]. It can also be inferred that the wear resistance of LM 25 aluminium alloy has been enhanced by retrogression at 200 °C.

4. Conclusion

In the present work, the effects of retrogression and re-aging on mechanical and wear properties of LM 25 aluminium alloy were investigated. The following conclusions are drawn:

- The tensile strength of LM 25 aluminium alloy initially increases at a retrogression temperature of 200 °C and decreases as the temperature increases. The highest tensile strength of 182 N/mm² was observed at a retrogression temperature of 200 °C. The tensile strength increase is about 47 % from the base tensile strength of 123.4 N/mm².
- The maximum hardness of 125 HV is observed in the specimen retrogressed at 200 °C. The hardness increase is about 44 % from the base hardness of 87 HV. The hardness decreases as the retrogression temperature increases above 200 °C.
- The retrogression at 200 °C enhances the wear resistance of LM 25 aluminium alloy. The minimum wear rate of 0.38 m³/m is observed with the load of 10 N and at a sliding velocity of 2 m/s at retrogression temperature of 200 °C and this is about 14 % less than the base alloy wear rate of 0.44 m³/m. The wear rate of alloy increase as retrogression temperature increases above 200 °C.
- Retrogression and re-aging of LM 25 aluminium alloy has no effects on the impact strength due to the brittle nature of alloy.
- The sleek and fine grain structure of evenly distributed silicon precipitates in aluminium matrix retrogressed at 200 °C improves the overall mechanical and wear properties.
5. References

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