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Experimental Analysis of Mechanical Properties on AA 6060 and 6061 Aluminum Alloys

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Abstract
Due to the substantial increased in demands of aluminum in industries like automotive industry and building industry, it is required for improvement of its mechanical properties by addition of suitable alloying elements to aluminum. The objective of this research is to study the effect of various alloys addition to aluminum and their effects on tensile strength, hardness and microstructure. The mechanical properties of AA 6060 and AA 6061 aluminum alloy have been characterized in terms of tensile strength and hardness. The result has been used to determine the tensile strength and % elongation of the specimen. From the results, it has been observed that mechanical properties of Al-alloys increasing up to 0.65% of Mg addition due to grain refinement, where as increase in Mg contents beyond 0.71% mechanical properties starts decreasing. The microstructure of the fracture surface after tensile strength has been examined using inverted microscope.
Keywords: Aluminum alloys, Mechanical properties, Microstructure, Fracture.

I. Introduction

The mechanical properties of metals and its alloys can be improved by a combination of metallurgical, manufacturing and design measures, which increase the reliability and service life of the component manufactured [1]. Due to good physical and mechanical properties of aluminum and its chemical composition imparts this widely used metal after the steel [2]. Aluminum and its alloys have high strength-to-weight ratio and other desirable properties like non-toxic, non-magnetic, high thermal and electrical conductivities, high corrosion resistance and easy to fabricate. By addition of silicon to aluminum, its strength-to-weight ratio can be improved and widely used for industrial application and home appliances and by introducing some other alloys like magnesium, iron and manganese to improve its mechanical properties so that it can be used for aircraft and space vehicles, construction and building materials, electrical transmission lines. Al-Mg-Si alloys (i.e. 6xxx series alloys) have widely used in automobile industry and building industry due to its medium strength, corrosion resistance and low cost. From many years extensive research going on the precipitation and aging behavior of Al- Mg-Si alloys has been detailed in [3, 4, 5]. Kasprzak et al. [6] reported the suitability of aluminum alloys for diesel engine applications at high pressures and temperatures by developing alloy with improved high temperature performance and properly heat treatment to improved properties upto 250^0C. Panigrahi and Jayaganthan [7] have presented the cryorolling of Al-Mg-Si alloys for improvement of mechanical properties, due to development of ultra fine microstructures and ageing treatment of alloys further increased its strength and ductility extensively. Kim et al. [8] studied the impact of equal channel angular pressing (ECAP) combined with ageing treatment on 6061 Al alloy and found that its strength significantly increased at room temperature. Al 6061 alloy is mainly composed of Al-Mg-Si-Cu and suitable for automotive and aerospace applications. The presence of Fe in aluminum and its alloys is common that is not easily removed but has unfavorable impacts on ductility and castability, especially in Al-Si based alloys Belov and Aksenov [9]. They reported that, increase in iron content decreased gradually ultimate tensile strength, due to the presence of intermetallics in the matrix. Table 1 show the chemical analysis of HE 20 grade or 6061 Al alloy and $AlMgSi_{0.5}F_{22}$ or AA 6060 aluminum alloy by % weight basis of each element.

Table 1. Chemical composition of aluminum alloys

Alloy Name	Cu	Mn	Si	Mg	Zn	Fe	Al
HE 20 or AA 6061	0.38	0.44	0.47	0.75	0.002	0.28	Balance
AA 6060	0.005	0.03	0.44	0.47	0.004	0.35	Balance

The main objective of this research is to investigate the influence of alloying elements on the tensile properties and hardness of aluminum alloys and its significance on the microstructure of the aluminum alloy. This study also focuses the impact of dimensions of the specimen on the strength and ductility of the alloy.

II. Experimental Materials and Methods

This research has considered aluminum alloys to study the effects of added alloys on mechanical properties of the material. Pure aluminum is a weak and ductile material, but by adding small % of impurities in aluminum its tensile strength as well as hardness increased considerably has been explained by Bolton [10]. Many researchers are focusing on Al alloys of 6000 series due to its application in automobile and construction industry. The chemical compositions of two Al alloys considered for this research have been shown in Table 1.

The tensile test is used to determine the tensile strength for a material and also measure the elongation at fracture. During the test, a single-axis stress state has generated by applying an external load to the specimen in a longitudinal direction. This results in a uniform normal distribution of stress across the test cross-section of the specimen. The load on the specimen is increased slowly and continuously by turning the hand wheel until it breaks. The resulting maximum test force is a measure of the material's strength called ultimate tensile strength R_m in N/mm^2 is calculated from the maximum test force F_B in N, determined from the force-elongation diagram and the initial cross-section A_0 of the specimen in mm^2. The elongation at fracture is the ratio of the change in length of the specimen to its original length L_o and is calculated by measuring the length L_u of the specimen after fracture. After fracture, the two ends of the specimen are placed together cleanly at the fracture point and the distance between the two measuring marks has been measured. The result of tensile test has been represented in a stress-elongation diagram. From the graph, the ultimate tensile strength R_m, the proportionality limits $R_{p,}$ the yielding point R_e and the fracture strength R_f can be calculated and noted in the Table. Specimens of each material have been tested at room temperature on GUNT Universal Testing Machine (UTM) with constant crosshead movement of 2 mm/min for tensile strength of the material. An extensometer has been used to calibrate and measure the sample strain upon loading. Tensile tests were performed at room temperature on 6 mm diameter cylindrical specimen with a gauge length of 30 mm for AA 6060 alloy specimen and gauge diameter 5.8 mm and length 33 mm for 6061 alloy. The tests were run under constant and continuous application of load at initial strain rate of 1×10^{-4} s^{-1} on UTM. The specimens were loaded continuously until failure. The fracture surface of the specimens after tensile test were examined the microstructure using inverted microscope after polishing it using keller etchent (6 ml HNO_3, 3 ml HCl, 2 ml HF and 200 ml distilled water) for 15 seconds.

2.1 Tensile Test

The standard specimens for materials aluminum has been used to find tensile strength of the materials. Two test pieces for each material of aluminum: one specimen is HE-20 grade or 6061 Al alloy and other is $AlMgSi_{0.5}F_{22}$ or AA 6060 Al alloy have been used for determining the tensile strength of the materials on GUNT Universal Testing Machine (UTM). The mechanical behavior of each specimen has been determined from tensile test data, one specimen of diameter 6 mm and 30 mm gauge length (L/D ratio is 5) with 64 mm of total length for AA 6060 and gauge length of 33 mm and diameter of 5.8 mm with total length of 67 mm for 6061 alloy has been used for experimental analysis. The tensile test has been carried on UTM of 20 KN capacity at across head speed of 2 mm/min, where the load deflection curve obtained for each specimen. Data were generated during the test like applied load, elongation, stress and % elongation in table and the graphs and curves have been plotted for each specimen by continuous application of load until fracture. The specimens used for the test were received in the form of cold-rolled plate, which further machined from plate to cylindrical specimen of gauge length 30 mm and 33 mm for AA 6060 and 6061 alloys and diameter of 6 mm and 5.8 mm consecutive alloys. The specimens were annealed, one specimen of AA 6060 annealed at temperature 200^{0}C for 60 minutes and then quenched in water. After annealing where as 6061 alloy annealed at 245^{0}C for 60 minutes. It is understood that addition of more %wt of Mn increased the tensile strength. Lee et al. [11] investigated the influence of solid solution of Mn on tensile properties of Al alloys after cold-rolling and recovery annealing. They found that Mn content at same annealing temperature significantly increased the tensile strength. Omotoyinbo and Oladele [12] have inspected the impact of Mg content in Al-alloys on mechanical properties. They found that up to 0.65%Mg addition increase in tensile properties, where as at 0.751%Mg content, cause decrease in the tensile properties.

2.1.1 Specimen details for $AlMgSi_{0.5}F_{22}$ or AA 6060 Al alloy

Gauge length (l_0) = 30 mm, gauge diameter (d_0) = 6 mm and increased length (l_u) = 34.7 mm reduced diameter (d_f) = 5 mm.

$$A_o = \frac{\pi}{4} d_i^2 = \frac{\pi}{4}(6)^2 = 28.26\,mm^2, \quad A_f = \frac{\pi}{4} d_f^2 = \frac{\pi}{4}(5)^2 = 19.63\,mm^2$$

$$Strain(\varepsilon) = \frac{l_u - l_o}{l_o} = \frac{34.7 - 30.0}{30.0} = 0.1567, \quad \%\,reduction\ in\ area = \frac{A_o - A_f}{A_o} \times 100 = 30.54$$

2.1.2 Specimen details for HE 20 or 6061 Al alloy

Gauge length (l_0) = 33 mm, gauge diameter (d_0) = 5.8 mm and increased length (l_u) = 41.0 mm reduced diameter (d_f) = 3.5 mm.

$$A_o = \frac{\pi}{4} d_i^2 = \frac{\pi}{4}(5.8)^2 = 26.41\,mm^2, \quad A_f = \frac{\pi}{4} d_f^2 = \frac{\pi}{4}(3.5)^2 = 9.62\,mm^2$$

$$Strain(\varepsilon) = \frac{l_u - l_o}{l_o} = \frac{41.0 - 33.0}{33.0} = 0.2727, \quad \%\,reduction\ in\ area = \frac{A_o - A_f}{A_o} \times 100 = 63.57$$

Figure 1 show the experimental setup for tensile test on UTM of each specimen and fractured specimens after the test.

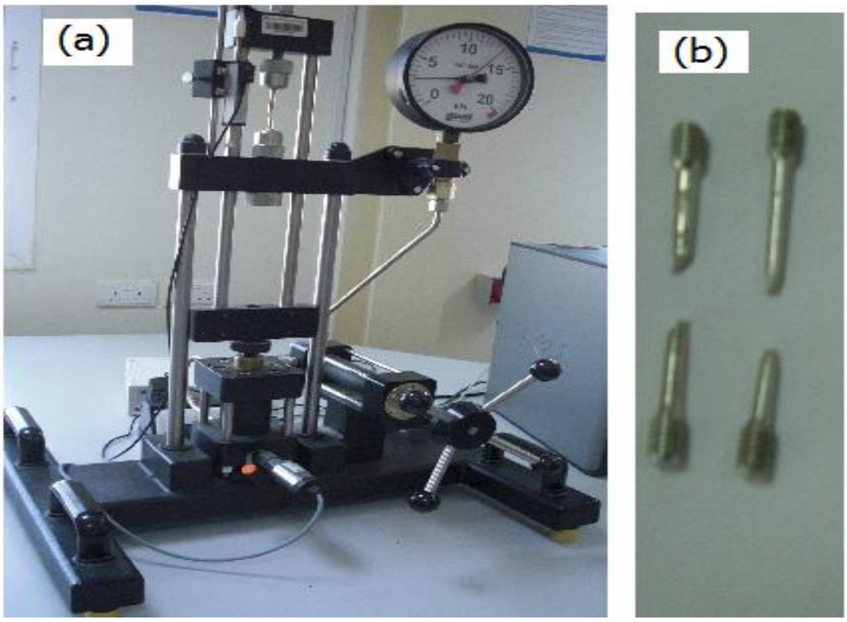

Fig. 1 – (a) Universal Testing Machine (UTM) and (b) specimen after fracture

The experimental result of each specimen has been presented in table. Table 2 shows the experimental results for $AlMgSi_{0.5}F_{22}$ or AA 6060 aluminum material. Table 3 shows the experimental results for HE-20 grade aluminum (6061).

Table 2. Tensile Test result for AA 6060 aluminum alloy

S. No.	Load P (N)	Elongation e (mm)	Stress $\sigma = \frac{P}{A_0}(N/mm^2)$	% Elongation $EPS = \frac{e}{l_0} \times 100$	Imp. Stress (N/mm^2)
1	10	0.024	0.339	0.081	
2	2128	0.366	75.227	1.221	
3	5235	0.513	185.140	1.709	R_p = 185
4	8638	0.684	305.516	2.279	R_e = 306
5	9817	1.099	347.223	3.662	
6	10211	1.392	361.126	4.639	
7	10450	2.148	369.603	7.161	
8	10575	3.003	374.011	10.010	R_m = 374
9	10479	3.516	370.620	11.719	
10	9875	4.199	349.258	13.997	
11	9070	4.639	320.774	15.462	R_f = 321

Table 3. Tensile Test result for HE-20 or AA 6061 grade aluminum alloy

S. No.	Load P (N)	Elongation e (mm)	Stress $\sigma = \frac{P}{A_0}(N/mm^2)$	% Elongation $EPS = \frac{e}{l_0} \times 100$	Imp. Stress (N/mm^2)
1	268	0.000	10.160	0.000	
2	1218	0.113	46.12	0.377	
3	3384	0.415	128.094	1.258	R_p = 128
4	4094	1.025	154.947	3.107	R_e = 154
5	4602	1.807	174.179	5.475	
6	4928	2.588	186.517	7.842	
7	5110	3.491	193.412	10.579	
8	5129	4.224	194.137	12.799	R_m = 194
9	5120	5.054	193.774	15.314	
10	4880	5.908	184.703	17.904	
11	4218	6.836	159.664	20.715	R_f = 160

2.2 Hardness

Hardness of material imparts most important properties for determining the strength and resistance to wear and scratching of the surface of the material. Hardness of a material can be defined as the ability of a material to resist indentation or deformation marked on the surface with an indenter under load. Rockwell hardness of pure aluminum or AA 6060 and HE 20 or 6061 Al alloy has been determined using steel ball of $\frac{1}{16''}$ diameter and 60 kgf force. The Rockwell hardness was measured on the surface at five different locations then values were averaged and then noted for each specimen. The hardness of pure aluminum or AA 6060 is 76.8 HRF and that of 6061 or HE 20 Al alloy is 36.2 HRF. The hardness of Al alloys varies due to the presence of Fe content more in AA 6060 compare to 6061 Al alloy. According to Man et al. [13], the hardness of aluminum alloys of Al-Mg-Si with the addition of 0.6% addition of Cu is more than that of aluminum alloy without Cu during isothermal treatment. The hardness of Al alloy depends on the % addition of Fe content, as it changes the phase. The addition of Fe at room temperature can not improved the tensile ductility where as its compressive strength and hardness increased slightly presented by Munroe et al. [14]. Copper has high solubility in Al alloy and as its content increased in Al alloys, their strength, hardness, machinability and fatigue and creep resistance significantly improved [15].

III. Results and Discussions

3.1 Microstructure

The microstructure of aluminum alloys imparts more on mechanical properties of aluminum. After tensile test, the fractured specimens were neatly cleaned and polished for microscopic observation of the fracture surface. Figure 2 shows the microstructure of fracture surface after tensile test of aluminum alloys HE 20 and AA 6060. The microstructure observed by inverted microscope of specimen after fracture and identified the aluminum dendrites, surrounded by silicon and magnesium alloys in grey phase. Some bright phase has been observed in HE 20 alloys with zinc and some other phases of Si-Cu and Si-Mg-Fe were also observed in pure aluminum alloy. The addition of Cu to Al-Si alloy will strengthen the material via the precipitation of Al_2Cu as well as improved the corrosion resistance [16]. The strength of aluminum alloys can also be improved by the addition of Mg through the precipitation of fine Mg_2Si and thus strength and recovery characteristics of Al alloy can be improved at increased temperature also [17]. Lee et al. [11] and Nam and Lee [18] have explained that addition of 0.7 wt% Mn to Al-Si alloy improved the yield strength and ultimate tensile strength of the alloy without decreasing ductility via Al_2Mn precipitation. They also explained the impact of iron addition on aluminum alloys, which change the appearance of microstructure lattice and reduce the ultimate tensile strength. Gubicza et al. [19] reported that strength of Al alloy can be improved by the interaction of Mg solute atoms and dislocations during initial stage of plastic deformation, this resulting increment in flow stress with increasing temperature. They also found that Mg addition has significant influence on the recovery properties of Al alloys.

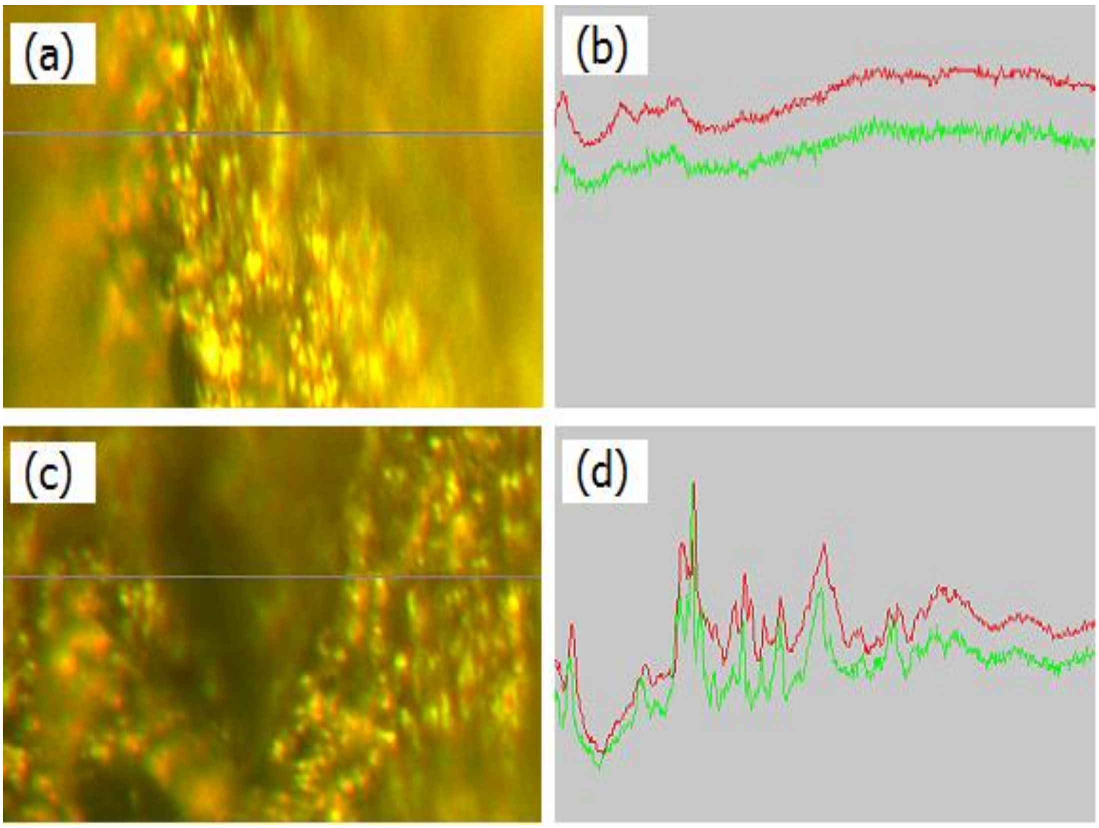

Fig. 2. Typical microstructure of aluminum alloys with addition of various alloying elements: (a) $AlMgSi_{0.5}F_{22}$ or AA 6060 aluminum alloys, (b) show the bright primary phases containing alloys in AA 6060 on line across, (c) HE 20 grade or 6061 aluminum alloys, (d) show the bright primary phases containing alloys in HE 20 on line across.

3.2 Tensile Properties

The tensile properties of two Al alloys at a strain rate of 1×10^{-4} s^{-1} on UTM has been tested and generated data for both alloy has been shown in Table 2 and 3. Figure 3 shows the stress-strain curves based on the generated data has been plotted. From the graph, it has been observed that AA 6060 Al alloy has low ductility and more tensile strength and hardness compare to 6061 Al alloy. Figure 4 shows the comparative diagram of above two Al alloys and plotted in software supporting the UTM test. Table 4 shows the comparative observations of mechanical properties during the test.

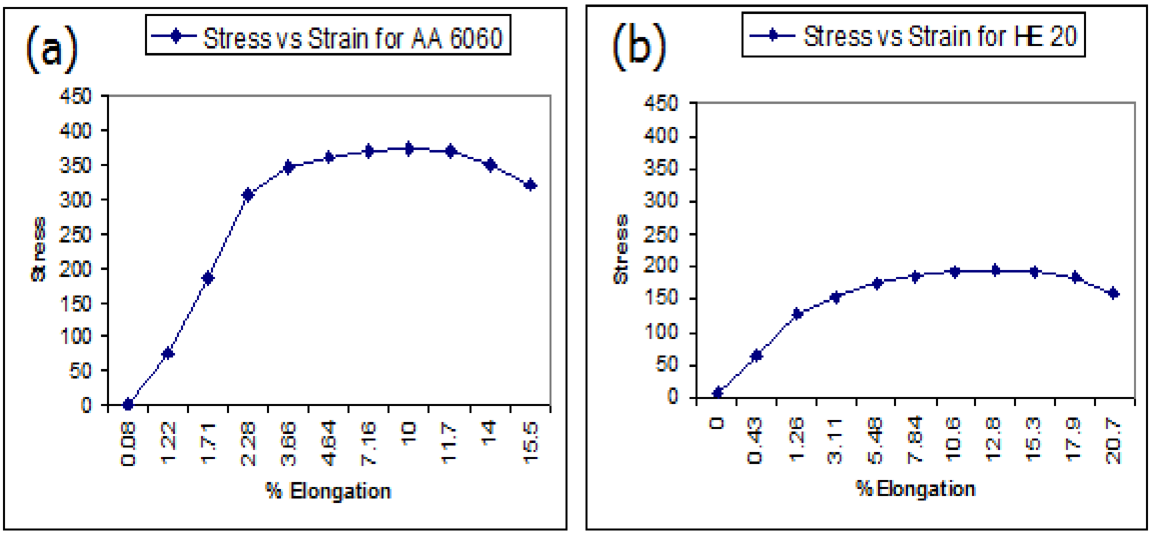

Fig. 3. Typical stress-strain curves for (a) pure aluminum or AA 6060 Al alloy and (b) HE 20 or 6061 Al alloy at strain rate of $\mathbf{1\times10^{-4}\ s^{-1}}$.

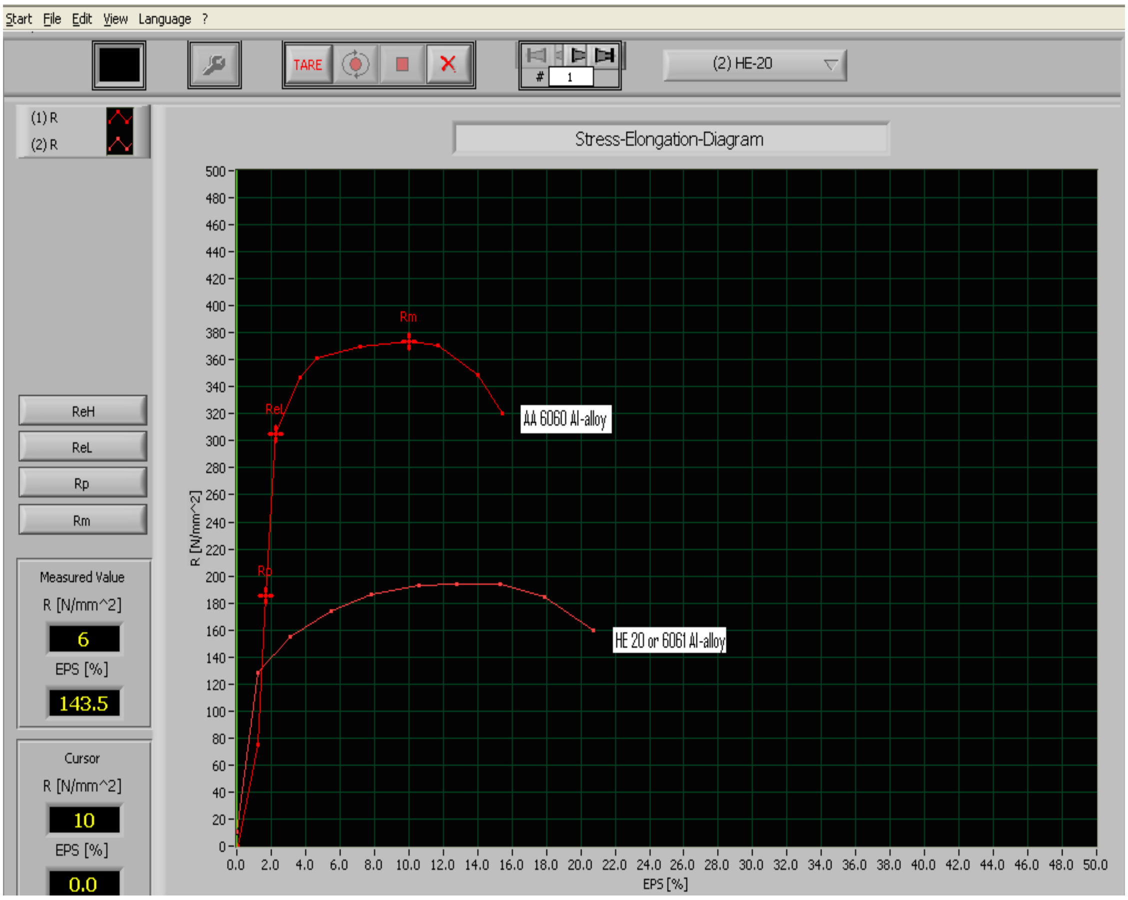

Fig. 4. Comparative study of stress – elongation graph for AA 6060 Al alloy and HE 20 or 6061 Al alloy.

Specimen dimensions also influence the tensile strength and ductility of the material. As the gauge length increased, reduced the effect of localized deformation at necking on total elongation i.e. by increasing the gauge length % elongation of the specimen will reduce. The strain-hardening capacity of material also impacts on the % elongation. During performing the test, increase in strain rate, significantly increased the flow stress.

Table 4. Tensile Test observation of two specimens

Material Properties		**$AlMgSi_{0.5}F_{22}$ (AA 6060)**	**HE 20 (6061)**
Young modulus	N/mm^2	185	128
Yield stress	N/mm^2	306	154
Ultimate tensile strength	N/mm^2	374	194
Tensile Strength at Fracture	N/mm^2	321	160
Total Elongation	%	15	21
Rockwell Hardness	HRF	76.8	36.2

IV. Conclusion

This study investigated the influence of alloy elements addition on the tensile properties and hardness of two specimens of different compositions, gauge diameter and gauge length. The mechanical properties of Al AA 6061 alloy have low values of tensile strength and hardness. On the other hand, AA 6060 Al alloy have significantly high tensile strength, yield strength and hardness with lower ductility. The increased %wt content of Mg up to 0.65 % is significantly improving tensile strength, yield strength and reducing elongation of Al alloy, if annealed at same temperature. Where as, %wt contents of Mg at 0.71% or above cause to decrease in strength and mechanical properties of aluminum alloys. Two specimens have annealed at different temperature, as temperature increased beyond 180^0C for same composition have low tensile strength.

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