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Experimental Analysis on the Forging Process of Al 6061 and Al 7075 Aluminium Alloys

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Abstract

The metal forming processes of 6061 and 7075 aluminium alloys by forging at elevated temperatures was analysed experimentally. In forging operation, folding, under filling, broken streamline, fracture, coarse grain, and other micro and macro flaws are simply caused due to the deformation properties of aluminium alloys, including slight forge able temperature part, rapid heat depletion to dies, strong bonding, maximum strain sensitivity and high flow resistance. Experimental analysis for different specimens were carried out and compared in terms of forging load to deformation by using pneumatic hammer and hydraulic press and finally after the study it was found out that resistance to deformation rises with the decrease in forging temperature and rise in strain rate in the case of both 6061 and 7075 aluminium alloys and flow stress decreases for both the alloys (Al 6061 & Al 7075) after 50% deformation with showing maximum forge ability (minimum flow stress) under following conditions with minimum reduction of 30% and forging temperature of 450℃.

Keywords: Aluminium alloys; Forging load; Deformation; Strain rate; Flow stress; Pneumatic hammer; Hydraulic press

Introduction

According to the sources, one of the plastic deformation process is forging. In the forging process, straightforward billet geometry is converted in to a complicated geometry by putting in the necessary pressure on the specimen with the help of forging instruments such as presses and hammers. Forging process generates finished items which show better mechanical and metallurgical properties rather than items which are made by machining or casting. Forging operation generally build some or empty scrap and creates the end part geometry in an exceedingly short time period, basically in single or multiple strokes of the hammer or press [1]. Compression analysis was performed on Al-Mg-Si aluminium alloy (6061 alloy) by using feeble thermo mechanical simulator-3500 (TMS) by Rahul D Dongre and Swati Salunkhe [2] at 350°C, 400°C, 450°C temperatures and with strain rates of 0.2 and 2, for a allotted nominal strain from the value chosen. As the strain increased and temperature decreased the stress due to the flow raised. In contradistinction, during the temperature at 440°C, stress increased with the strain rate due to the rise in the breakdown density & breakdown multiplication rate. Woei-Shyan Lee, et al., [3] has studied experimentally the effective impact properties of 7075 aluminium alloy using a split Hopkins bar, micro structural observations after the tests revealed that the size of the primary coarse equi-axial grains was reduced as the strain and temperature raised due to effective recrystallization. In contrast, the second phase increases in size in response to increasing strain rate and temperature. The deformation of aluminum AA 6061-T6 alloy under high impact condition was determined by Gazebo Wasabi, et al., [4] performing full field measurement of strain on the surface of the specimen. The type of shear band that initiates in the aluminum sample depends on the impact velocity or strain rate at which the impact is performed. The micro structural evolution and the room temperature mechanical properties of the 7075 Al alloy was investigated by A. Abolhasani, et al., [5] upon rolling at different conditions. The results indicated that the room temperature mechanical properties of the alloy are significantly influenced by the rolling temperature in the temperature range of 250-450°C. The quasi-static and dynamic yield and flow behaviour of Al-6061-T6 and Al-6061-OA are investigated by Xin Tang [6] under uni-axial tension loading at the test temperatures range from room temperature down to -170°C. At all strain rates, Al-6061-T6 showed high strength but lower ductility than Al-6061-OA. The mechanical behaviour of any material can be described using several tests, such as, compression tensile, hardness test, etc. Here, cold and hot compression tests and hardness measurements were utilized by Tareg S. Ben Naser [7].

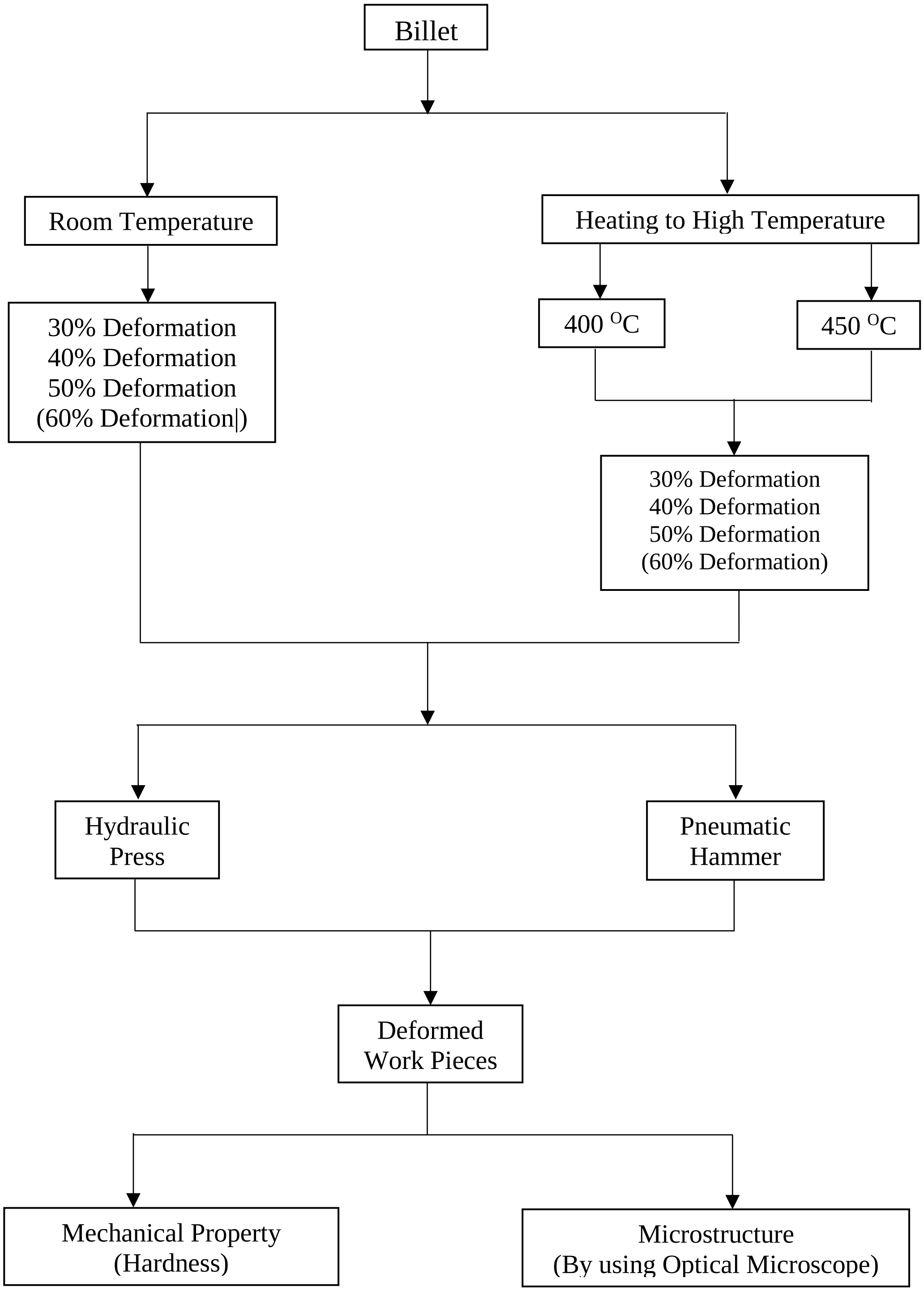


Figure 1: *Flow Chart for Methodology.*

The investigated material for the research was the Al 7075 alloy in the early state and multiple forged state. Comparing the material result by using sin hyperbolic constitutive equation with the preceding results, it can be declared that the sin hyperbolic function is more dependable than the exponential function to foretell the experimental response of the specimen. In order to study the work ability of the 7050 aluminum alloy, the flow stress behaviour has been studied by a set of isothermal hot compression tests [8]. The strain has shown a significant influence on the material constants, and true stress–true strain curves have revealed that the flow stress was sensitive to the deformation strain rate and temperature for the 7050 aluminium alloy. Dyi-Cheng Chen, et al., [9] studied and utilized finite element software to simulate the plastic deformation behaviour of a 7075 aluminium alloy during the forging process. Results showed that the optimal parameter settings for the forging process had three different combinations. The experimental variable on the forging temperature and experiment results are determined by suitable conditions in hot forging on two types aluminum alloys AlSi1Mg:Al6063 andAlZn5.5MgCuAl7075 by S Sopha, et al., [10]. The results of the experimental revealed that the forming temperature effected to the force from Hot forging of aluminum alloys Preheat temperature were higher value, done the forming force were lower and the forming temperature also effected to the material hardness. A medallion with intricate features down to 0.25 mm was designed using solid works 3D modelling software. The model was then transformed into a die set by aluminum precision products (APP) using super forge software. Results from sixteen tests showed the optimum preheat temperature was 490°C for the aluminum charges and forging dies, and 300°C for the forging press platens [11]. The forge ability of aluminum metal matrix composites, which are made by powder metallurgy method, are greatly dependent on the size and percentage of reinforcement materials, compacting load, wintering temperature and soaking time [12]. The deformation behaviour and micro structural evolution of a 7075-T6 aluminum alloy have been explored by M.R. Rokni et al. [13] through applying hot compression tests at different temperatures and strain rates (450°C, 500°C, 520°C, 550°C, 580°C and 0.004, 0.04 and 0.4 s^{-1}), outcomes showed that the recrystallized shape has been in spheroidzed state even in normal solid temperature range due to the liquid pressure and the specimen size was decreased with the rise in the strain rate. Abood, et al., [14] investigated on the low cycle fatigue of aluminum alloy AA-6061 in three different conditions such as annealing, T4 and T651. Annealing has the higher value of transition fatigue life in the case of aluminum alloy AA-6061.

The main objective is to study the forging behaviour of two different aluminium alloys one is 6061 which has low strength and another is 7075 which has high strength under different conditions. The (Figure 1) shows the research methodology for conducting the tests and analysis on the aluminium alloys.

Figure 2: *Aluminium alloys 7075 and 6061 specimens.*

Figure 3: *Standard work piece for upsetting*

Experimental Details

Sample preparation

Aluminium 6061 and 7075 alloys were supplied by Bharat aerospace metals India private limited, Mumbai as represented in (Figure 2). The specimen was considered in a pliable form and placed in a furnace at 529.66°C for one and half hour. Then, it's dropped into a quench tank to rapidly cool, with this step taking no more than six seconds. From there, it's formed or straightened and then allowed to set for a designated amount of time. After that, the aluminium part can undergo an aging heat treatment, where it is placed in 176.66℃ to 260℃ for 12-24 hours. Aluminium Alloys 6061 and 7075 are used for the experimental work having chemical compositions represented in (Table 1) and the dimensions of the aluminium alloys 7075 and 6061 specimens are presented in (Table 2). The wrought aluminium alloys are cut into 13 pieces/rod for a length of 65 mm per piece as shown in the (Figure 3) and it is machined to length of 60 mm having L/D ratio 1.5. As L/D ratio is limited to 1.5 because of the limitation in hydraulic press that the distance between the two dies is 75 mm only, so we can do upset operation for a maximum length of 70 mm.

Forging equipment

The general arrangement of the pneumatic hammer is shown in (Figure 4). Stainless steel test bearing shaft is held by a pair of bearings. Load is transmitted to the test bearing via three elements in series such as load cell, tie rod and sub-assembly incorporating tension performance nuts, self-straightening ball bearings and two decoupling springs. These springs, with a stiffness much lower than that of the test bearings, the weight of the pneumatic hammer used for the tests was 250 Kg. The tie rod is spirally detected by an innately compensated guide air bearing housed in another cross beam. When it comes to the point of hydraulic press it was weighed about 150 tonnes and is based on the motion of a hydraulic piston guided in a cylinder. Hydraulic presses are essentially load-restricted machines, their capacity for supporting out a forming process is limited by the high obtainable load. Ring stopper and loading of work piece on the stopper is shown the (Figures 5 and 6). Aluminium alloy 6061 is forged under cold condition to the maximum capacity of the hydraulic press till it breaks as shown in (Figure 7), but it is not failed under maximum load rather than deformed to 70% due to low hardness and high ductility. Aluminium alloy 7075 is forged under cold condition in hydraulic Press till it breaks, but it is shear failed at a deformation of 25% due to high hardness and low ductility.

So to decrease the hardness and increase the ductility for 7075 alloy, both the alloys were given annealing treatment as per the cycle.

Metallographic study

The samples for Microstructural observation has been cut from the deformed portion. The samples are grinded & polished using emery papers of grades 120, 220, 320, 400 and 600. After paper polishing the samples are polished in fine cloth using alumina powder with water. Finally, samples are polished by diamond paste. Samples have been polished so that face can be seen like mirror. If there are any scratches are observed they will be removed by polishing them on 600 emery paper and finished touch on cloth polishing. After completion of cloth polishing the samples are etched with keller’s reagent (distilled water of 190 ml, Nitric Acid of 5 ml, HCL of 3 ml, HF of 2 ml) for 10-30 seconds and wash in warm water. The microstructures of polished samples were observed using the optical microscope at a different magnification like 100X and 400X and the photographs are obtained by camera which is fitted with optical microscope.

Results and Discussions

Forging of aluminium alloy 6061

Forging of aluminium alloy 6061 in hydraulic press: Aluminium alloy 6061 was deformed at different temperatures (Room Temp, 400℃ & 450℃) and were deformed at different degree of deformations (30%, 40%, 50% & 60%). The pressure required for deformation was measured from the dial indicator fitted in the Hydraulic Press and then it was converted into load. Flow stress was calculated from load values. Flow stress calculation for 30% deformation at room temperature is shown below and flow stresses for remaining deformations were calculated similarly.

$$\text{Flow Stress } (\sigma) = \frac{\text{Force (F)}}{\text{Area of cross-section after deformation (A)}} \quad (1)$$

Flow stress for 30% deformation at room temperature:

(Table 3) shows the variation of load and flow stress for Al 6061 alloy deformed at different amount of deformations and at different temperatures in hydraulic press. From the data analysis as shown in (Figure 8), it is clear that the force required to deform the aluminium alloy 6061 increases with increase in rate of deformation. For any particular deformation rate, the force required for forging decreases with increase in forging temperature.

For all of specimens, after yielding the flow stress reduces monotonically with various softening rates. Flow stress decreases with increase in temperature. In cold forging, the flow stress curve is continuously decreasing, but in hot forging flow stress increases up to 50% deformation and then decreases due to dynamic softening. (Table 4) shows that the effect of deformation on mechanical property (hardness) deformed at various temperatures and different deformations for Al 6061 in hydraulic press. Data analysed in the graph as represented in (Figure 9) shows that the hardness value is continuously increasing with respect to deformation rate due to strain induced hardening for higher percentage of deformation. Hardness values for 6061 alloy are decreased with increasing temperature, but at room temperature the values are less when compared with the deformation at 400℃.

Forging of aluminium alloy 6061 in pneumatic hammer: It is unable to find out the load required for forging, as there is no dial indicator fitted to the Pneumatic Hammer. Hence, in this case, only effect of deformation on mechanical property was studied. Shows that the effect of deformation on mechanical property (Hardness) deformed at various temperatures and different deformations for Al 6061 in pneumatic hammer (Table 5) (Figure 10).

Forging of aluminium alloy 7075

Forging of aluminium alloy 7075 in hydraulic press: Aluminium alloy 7075 was deformed at different temperatures (Room Temp, 400℃ & 450℃) and were deformed at different degree of deformations (30%, 40%, 50% & 60%). The pressure required for deformation was measured from the dial indicator fitted in the hydraulic press and then it was converted into load. (Table 6) shows the variation of load and flow stress for Al 7075 alloy deformed at different amount of deformations and at different temperatures in hydraulic press. From the data analysis as represented in (Figure 11), it is clear that the force required to deform the Aluminium alloy 7075 increases with increase in rate of deformation. For any particular deformation rate, the force required for forging decreases with increase in forging temperature. For all of specimens, after initial yielding, the flow stress decreases monotonically with different softening rates. Flow stress decreases with increase in temperature. In cold forging, the flow stress curve is continuously decreasing, but in hot forging flow stress increases up to 50% deformation and then decreases due to dynamic softening. (Table 7) shows that the effect of deformation on mechanical property (hardness) deformed at various temperatures and different deformations for Al 6061 in hydraulic press. Data analysed by graphs shown in the (Figure 12) above state that the hardness value is continuously increasing with respect to deformation rate due to strain induced hardening for higher percentage of deformation. Hardness values for 7075 alloy are decreased with increasing temperature, but at room temperature the hardness values are similar when compared with the deformation at 450°C. Flow stress values of Al 7075 alloy at different temperatures are represented in the (Table 8).

Figure 4: *Pneumatic hammer and hydraulic press*

Figure 5: *Ring stopper and loading of work piece*

Figure 6: *Work Piece material with stoppers in hydraulic Press*

Figure 7: *7075 Al alloy work sample failed due to shear (it was upset at RT in HP)*

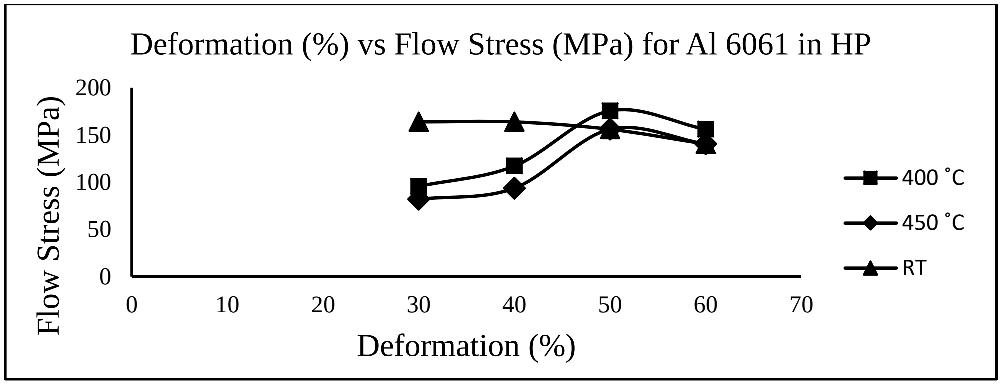


Figure 8: *Deformation (%) vs Flow Stress (MPa) for Al 6061 in HP*

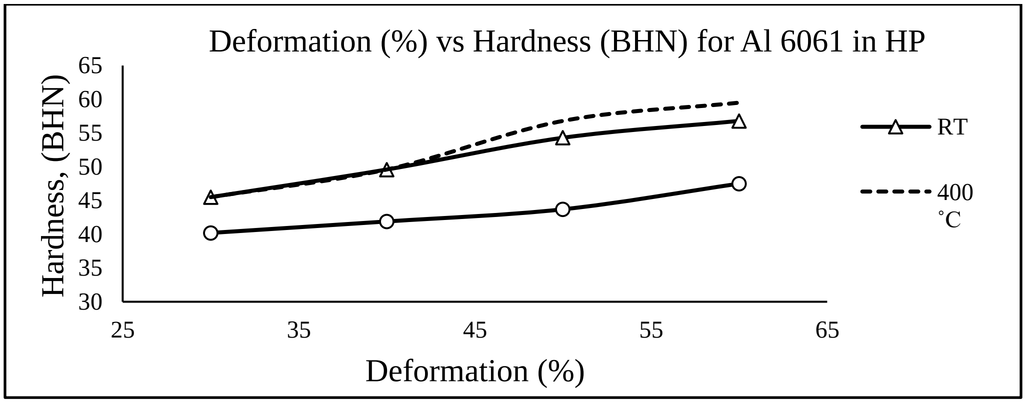


Figure 9: *Deformation (%) vs Hardness (BHN) for Al 6061 in HP*

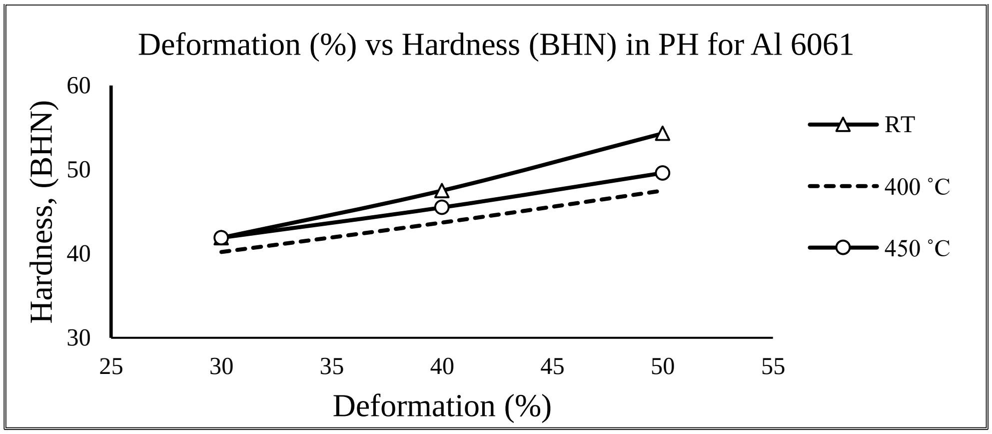


Figure 10: *Deformation (%) vs Hardness (BHN) for Al 6061 in PH*

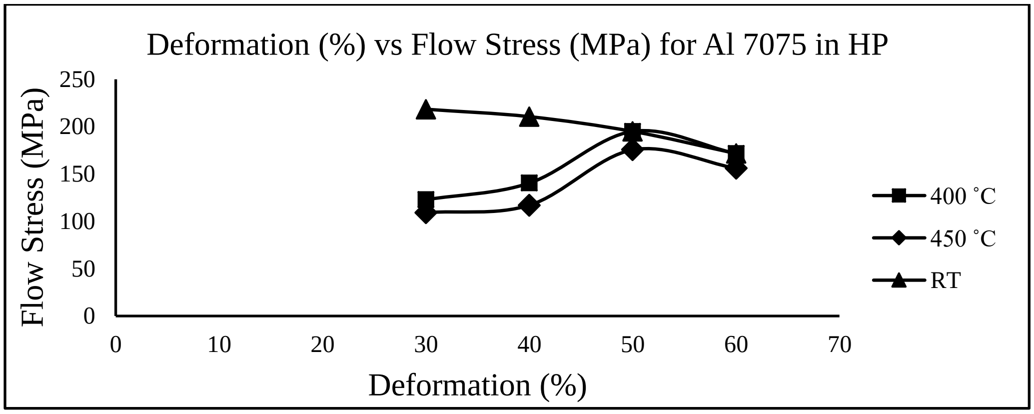


Figure 11: *Deformation (%) vs Flow Stress (MPa) for Al 7075 in HP*

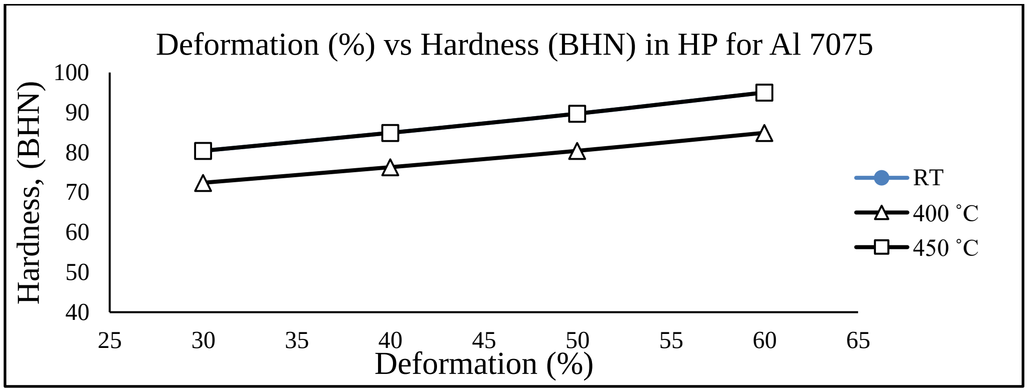


Figure 12: *Deformation (%) vs Hardness (BHN) for Al 7075 in HP*

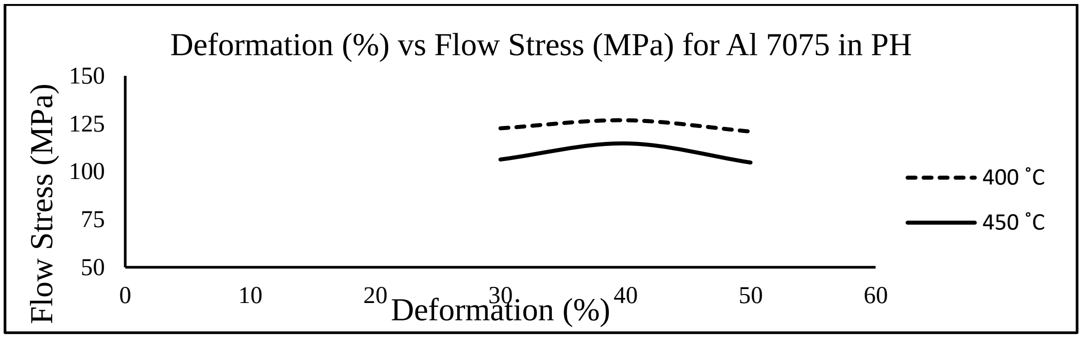


Figure 13: *Deformation (%) vs Flow Stress (MPa) for Al 7075 in PH*

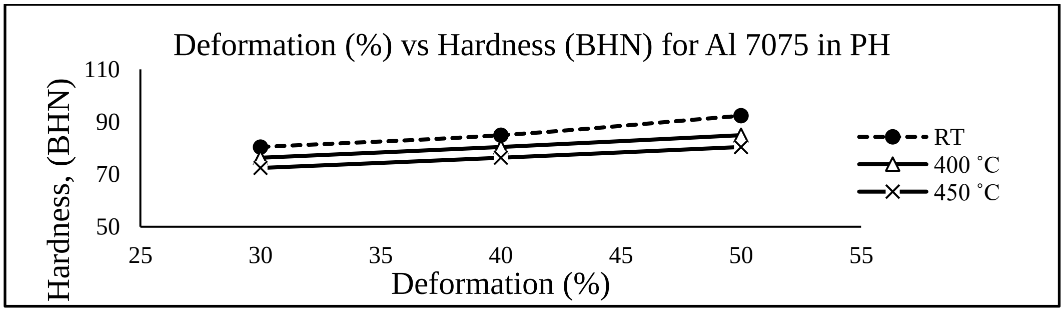
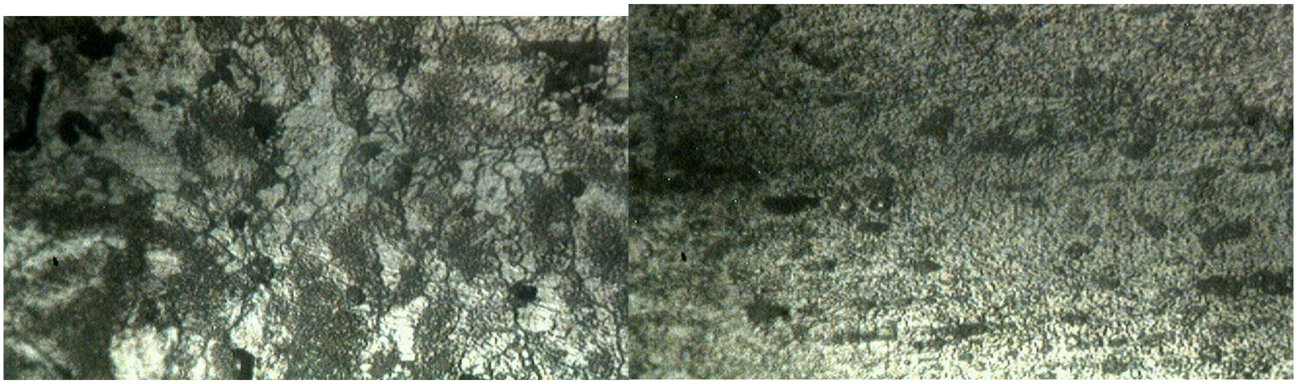
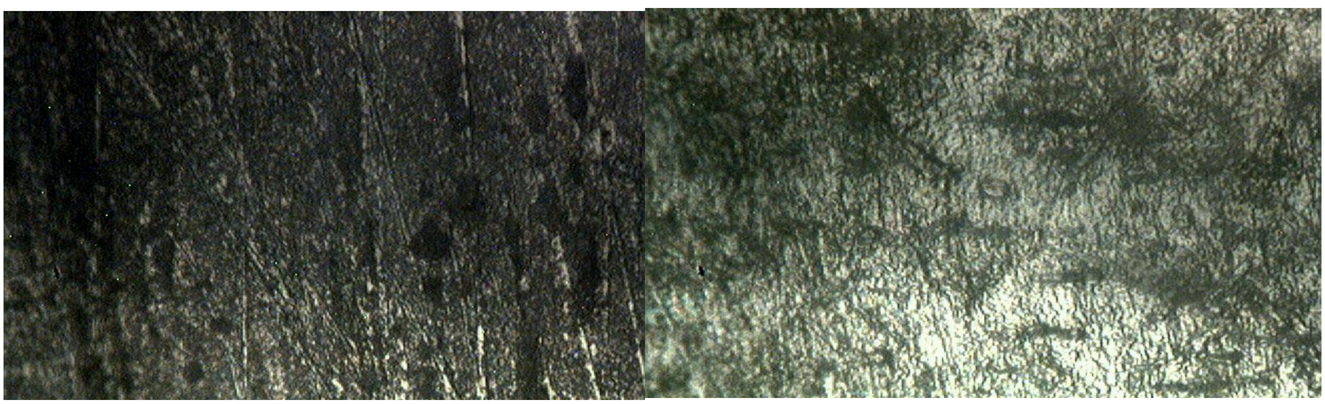


Figure 14: *Deformation (%) vs Hardness (BHN) for Al 7075 in PH.*



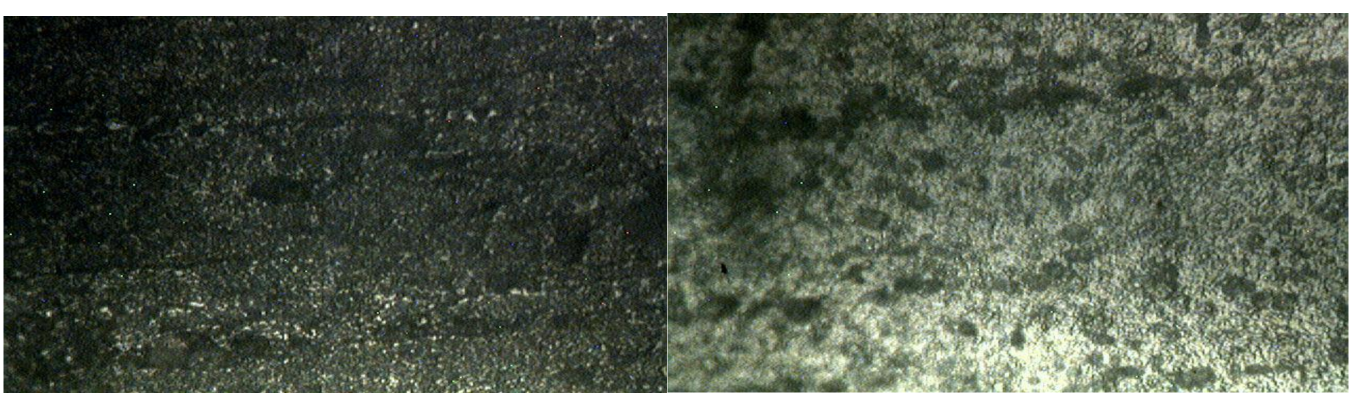
Initial Al 7075 at 400X **Initial Al 6061 at 400X**

Figure 15: *Initial microstructure of Aluminium 7075 and 6061 at 400ºC*



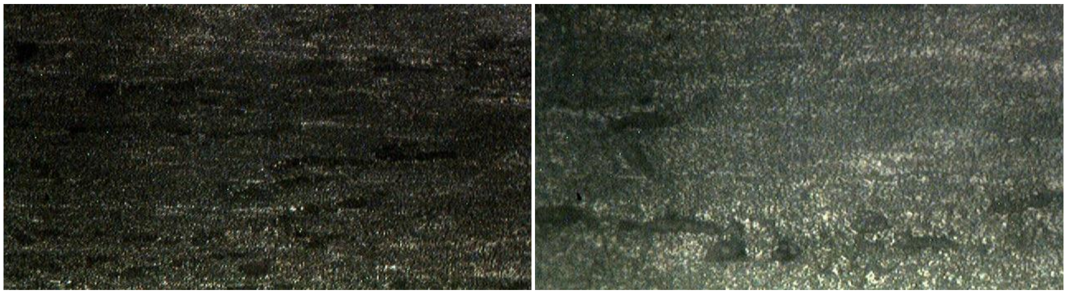
Al 7075 at 400X **Al 6061 at 400X**

Figure 16: *Aluminium alloys deformed to 50% in Hydraulic Press at 450 ºC*



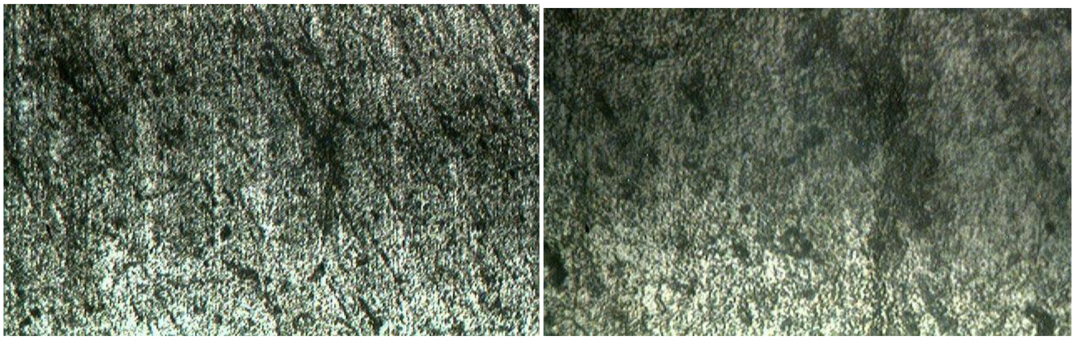
Al 7075 at 400X **Al 6061 at 400X**

Figure 17: *Aluminium alloys deformed to 50% in Hydraulic Press at Room temperature.*



Al 7075 at 400X **Al 6061 at 400X**

Figure 18: *Aluminium alloys deformed to 50% in Pneumatic Hammer at 400°C*



Al 7075 at 400X **Al 6061 at 400X**

Figure 19: *Aluminium alloys deformed to 50% in [pneumatic hammer at room temperature.*

Table 1: *Composition of Aluminium alloys.*

Elements	Alloy 6061 (Specification)	Actual 6061 Composition	Alloy 7075 (Specification)	Actual 7075 Composition
Si	0.4-0.8	0.64*	0.4 Max	0.07
Mg	0.8-1.2	1.0*	2.1-2.9	2.4
Fe	0.7 Max	0.14	0.5 Max	0.28
Cu	0.15-0.4	0.35	1.2-2	1.5
Mn	0.15 Max	0.03	0.3 Max	0.05
Cr	0.04-0.35	0.12	0.18-0.28	0.19
Zn	0.25 Max	0.03	5.1-6.1	5.85*
Ti	0.15 Max	0.05	0.2 Max	0.07
Al	Remainder	Remainder	Remainder	Remainder

Table 2: *Dimensions of the aluminium alloys 7075 and 6061 specimens.*

S.No	Parameter	Value
1	Length	3 Feet (915 mm)
2	Diameter	40 mm
3	No. of rods	4

Table 3: *Variation of load and flow stress for Al 6061 alloy deformed in HP.*

Temperature (ºC)	Deformation (%)	Force (kN)	Flow Stress (MPa)
25ºC	30	294	163.77
	40	343	163.77
	50	490	155.97
	60	539	140.37
400ºC	30	171.5	95.53
	40	245	116.98
	50	441	175.47
	60	490	155.97
450ºC	30	147	81.88
	40	196	93.58
	50	392	155.97
	60	441	140.37

Table 4: *Variation of Hardness for Al 6061 alloy deformed in HP.*

Deformation (%)	Hardness (BHN)		
	Room Temp.	400 ˚C	450 ˚C
30	45.5	45.5	40.2
40	49.6	49.6	41.9
50	54.3	56.8	43.7
60	56.8	59.5	47.5

Table 5: *Variation of Hardness for Al 6061 alloy deformed in PH.*

Deformation (%)	Hardness (BHN)		
	Room Temp.	400 ˚C	450 ˚C
30	41.9	40.2	41.9
40	47.5	43.7	45.5
50	54.3	47.5	49.6

Table 6: *Variation of load and flow stress for Al 7075 alloy deformed in HP.*

Temperature (ºC)	Deformation (%)	Force (kN)	Flow Stress (MPa)
25ºC	30	392	218.36
	40	441	210.56
	50	490	194.96
	60	539	171.57
400ºC	30	220.5	122.83
	40	294	140.37
	50	490	194.96
	60	539	171.56

450ºC	30	196	109.18
	40	245	116.97
	50	441	175.46
	60	490	155.97

Table 7: *Variation of Hardness for Al 7075 alloy deformed in HP.*

Deformation (%)	Hardness (BHN)		
	Room Temp.	400 ˚C	450 ˚C
30	80.4	72.4	80.4
40	84.9	76.3	84.9
50	89.7	80.4	89.7
60	95	84.9	95

Table 8: *Flow stress values of Al 7075 alloy at different temperatures.*

Strain	Flow Stress (MPa)	
	400ºC	450ºC
0.3	122.6	106.3
0.4	126.8	114.7
0.5	120.9	104.7

Table 9: *Load required for forging Al 7075 in PH at a strain rate of 10 s^{-1}.*

Strain	Force (kN)	
	400ºC	450ºC
0.3	264.1	228.99
0.4	318.6	288.27
0.5	364.62	315.76

Table 10: *Variation of load and flow stress Al 7075 alloy deformed in PH.*

Temperature (ºC)	Deformation (%)	Force (kN)	Flow Stress (MPa)
400ºC	30	264.1	122.6
	40	318.6	126.8
	50	364.62	120.9
450ºC	30	228.99	106.3
	40	288.27	114.7
	50	315.76	104.7

Table 11: *Variation of Hardness for Al 7075 alloy deformed in PH.*

Deformation (%)	Hardness (BHN)		
	Room Temp.	400 ˚C	450 ˚C
30	80.4	76.3	72.4
40	84.9	80.4	76.3
50	92.3	84.9	80.4

Table 12: *Flow stress values for different deformations and strain rates at 400ºC*

Strain rate	Deformation (%)	Flow Stress (MPa)
Hydraulic Press (0.25 s^{-1})	30	122.83
	40	140.37
	50	194.96
Pneumatic Hammer (10 s^{-1})	30	122.6
	40	126.8
	50	120.9

Table 13: *Comparison of Flow Stress values for Al 6061 and Al 7075.*

Deformation (%)	Al 6061			Al 7075				
	Hydraulic Press			Hydraulic Press			Pneumatic Hammer	
	RT	400ºC	450ºC	RT	400ºC	450ºC	400ºC	450ºC
30	163.77	95.53	81.88	218.36	122.83	109.1	122.6	106.3
40	163.77	116.98	93.58	210.56	140.37	116.9	126.8	114.7
50	155.97	175.47	155.97	194.96	194.96	175.4	120.9	104.7
60	140.37	155.97	140.37	171.57	171.56	155.9	------	------

Table 14: *Comparison of mechanical property (hardness) for Al 6061 and Al 7075*

Deformation (%)	Al 6061			Al 7075				
	Hydraulic Press			Hydraulic Press			Pneumatic Hammer	
	RT	400ºC	450ºC	RT	400ºC	450ºC	400ºC	450ºC
30	45.5	45.5	40.2	80.4	72.4	80.4	76.3	72.4
40	49.6	49.6	41.9	84.9	76.3	84.9	80.4	76.3
50	54.3	56.8	43.7	89.7	80.4	89.7	84.9	80.4
60	56.8	59.5	47.5	95	84.9	95	------	------

Forging of aluminium alloy 7075 in pneumatic hammer: It is unable to find out the load required for forging, as there is no dial indicator fitted to the pneumatic hammer. Hence the load required for forging in pneumatic hammer is calculated by using the flow stress values which are taken from the data book for a strain rate of $10s^{-1}$ [35], which were presented in the (Table 9).

Load is calculated as follows:

$$\text{Load} = k \times \sigma \times A \qquad (2)$$

Where,

σ = Flow stress, MPa.

A = Area of cross-section at a given deformation, mm^2.

k = constant and it depends on complexity of the job.

Generally, k =1.2 for simple upsetting operation.

(Table 10) indicates the variation of load and flow stress for Al 7075 alloy deformed at different amount of deformations and at different temperatures in Pneumatic Hammer. From the data analysis from the (Figure 13), it is clear that the force required to deform the Aluminium alloy 7075 increases with increase in rate of deformation. For any particular deformation rate, the force required for forging decreases with increase in forging temperature.

After initial yielding, the flow stress decreases monotonically with different softening rates. Flow stress decreases with increase in temperature. In hot forging flow stress increases up to 40% deformation and then decreases due to dynamic softening. (Table 11) shows that the effect of deformation on mechanical property (hardness) deformed at various temperatures and different deformations for Al 6061 in pneumatic hammer. Data analysed by graphs shown in the (Figure 14), show that the hardness value is continuously increasing with respect to deformation rate due to strain induced hardening for higher percentage of deformation. Hardness values for 7075 alloy are decreased with increasing temperature. Flow stress values for different deformations and strain rates at 400oC by using both hydraulic press and pneumatic hammer is represented in the (Table 12) below. Comparison of flow stress and hardness values for both Al 6061 and Al 7075 was performed and shown in the (Tables 13 and 14). Force required for forging 7075 aluminium alloy at room temperature is high when compared to forging at higher temperatures, as it is work hardened due to cold forging. The flow stress and the form of the flow curves is discreetly dependent on the strain rate and temperature. For controlled temperature, flow stress normally rises with the strain rate which is due to the rise in the dislocation solidity and the dislocation expansion rate. Flow softening appears more clearly with the temperature decreasing [15].

Microstructure analysis

The optical microstructures shown in the (Figures 15-19) indicates that the grains of billets compressed become more and more refined with strain rate increasing as well as the degree of dynamic softening and work-hardening higher.

Microstructures of forged work samples

Conclusion

In the current research forging behaviour of aluminium alloys 7075 and 6061 has been studied by using two different forging equipment's such as hydraulic press and pneumatic hammer to analyse the consequences of strain rate and forging temperature on flow stress. Experimental study was carried out to compare and validate the results and the following conclusions have been drawn:

- The stress value reduces due to the rise in temperature which will result in producing lower stress during flow process. But when it comes to the point of constant and steady temperature the flow stress rises with an increase in strain rate.
- It is noticed from the flow stress deformation graphs that the resistance to deformation rises with reduction in the forging temperature and rise in strain rate. Since that high temperatures and low strain rates provide an extended time for energy extraction and collection.
- The outcomes indicate that the temperature differences have an outstanding consequence on the dynamic softening rate. It is specified that the considerable dynamic softening rate which is associated with dynamic recrystallization guides the flow stress value to decrease gradually.
- The flow stress and shape of the flow curves are sensitively dependent on temperature and strain rate.
- Al 6061 and Al 7075 alloys showed maximum forgeability (minimum flow stress) under following conditions with minimum reduction of 30%, forging temperature of 450℃ with forging equipment such as hydraulic press
- Forge ability of Al 6061 is higher when compared to that of Al 7075 alloy, as the minimum flow stress for Al 6061 is 81.88 MPa and minimum flow stress for Al 7075 is 109.18 MPa.
- It is noted that the flow stress decreases for both the alloys (Al 6061 & Al 7075) after 50% deformation.
- Even though aluminium has FCC structure, it was noticed that the flow stress at room temperature is high. So the flow stress is reduced by annealing treatment.

Conflicts of Interest

The authors declare no conflict of interest.

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