Experimental Study of Forging Behavior of Aluminium Using Graphite Lubricants with Different Particle Sizes

Sivasubramanian A.[1], Purushooth B.[2], Uthami Raj V.[3], Muthukumar M.[4], Nagarajan N.[5]

[1]Associate Professor, [2,3,4,5]Student, Department of Mechanical Engineering, V V College of Engineering, Tisaiyanvilai, Thoothukudi, India.

E-mail: [1]siva@vvcoe.org

Abstract

Upset forging has been considered as an important metal forming process, since most closed die forgings commence with an upsetting phase and the deformation in upset forging may cause surface defects at the bulged surface. A series of investigations have been going on in bulk metal forming. Upset forging has become increasingly important in marine, aerospace and automobile applications. In this proposed work, intended to perform experiments and to generate data on cold upset forging of aluminium 6061 with graphite powder lubricant with different particle size applied on sides of the billet. The dimensions of aluminium pieces measured before upsetting. These aspect ratio of "1" will be prepared. The loads used for each deformation will be recorded from the dial indicator on compression testing machine. The relationship will also be established between the various bulge parameters namely loads, heights, surface roughness and the microstructure of materials under different lubricants with compared to dry condition. The relationship between Loads versus Displacement curve has been plotted for aspect ratio with lubricant different particle sizes conditions. Hardness will be measured for lubricant different particle sizes with aspect ratio at before and after forging.

Keywords: Upset Forging, Aluminium 6061, Graphite Lubricant, Barreling, Surface Roughness.

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1. Introduction

Upset forging is a widely used bulk metal forming process in which a cylindrical workpiece is compressed along its axis to achieve the desired shape and mechanical properties. This process is fundamental in the manufacturing of components such as bolts, fasteners, and structural parts, where improved strength and material utilization are required. However, during upsetting, non-uniform deformation occurs primarily due to friction at the die–workpiece interface, leading to a characteristic defect known as barreling.

The impact of friction on the process of deformation during metal forming operations is significant. Friction prevents free radial displacement of the material near the contacting surfaces but allows the deformation of the material in the center of the specimen. Therefore, conical areas of less deformed material are formed near the ends of the specimen, leading to the bulging of its surface. Such deformation is called barreling and results in uneven deformation of the specimen.

In order to mitigate the negative impacts of friction, lubricants have traditionally been used in forging operations. Lubrication not only reduces interfacial shear stress but also ensures proper metal flow and improved surface finish. Graphite lubricants, with their layered crystalline structure, thermal stability, and efficient lubricating ability, have gained popularity in various applications. Graphite efficiency as a lubricant can be affected by several parameters like particle size and distribution. The compression test has been an indispensable technique when it comes to studying the deformation behavior of materials in relation to loading conditions.

The results from these experiments give useful insight regarding flow stress and strain hardening in addition to being influenced by process parameters like strain rate and temperature. The compression test standards such as ASTM E9 help in providing reliable data. Aluminium 6061 was selected for this investigation because it is one of the most popular alloys that are extensively used in many engineering applications such as aerospace, automotive, and marine industries because of its favorable mechanical properties. However, it has a very sensitive deformation behavior when it comes to forging.

In this research, an experimental analysis is conducted for investigating the forging characteristics of Aluminum 6061 under both dry and lubricated conditions, in which Graphite powder particles with varying sizes are employed. In this way, the effect of lubricant particle size on the load versus displacement relationship and surface finish of samples, as well as the forging deformation process in general, will be assessed.

2. Literature Review

Research on aluminum matrix composites and lubrication systems has demonstrated significant improvements in tribological and mechanical performance through the incorporation solid lubricants and reinforcing particles. Initial observations made by Pillai & Pandey [6] found out that when graphite particles were added to aluminum matrix, there was an increase in wear resistance and affected the strength and ductility of both cast and forged composites. Additional research carried out on powder metallurgy processed aluminum-graphite composites observed that graphite acts as a tribofilm that leads to low coefficients of friction and increased wear resistance properties which prolongs the life span of components (Ravindran et al. [5]). In addition, Kumar et al. [3] observed that aluminum hybrid composites that had TiC and graphite as reinforcements had excellent wear resistance and mechanical properties in comparison to un-reinforced aluminum. Baradeswaran et al. [4] also found out that B_4C and graphite reinforcing particles greatly enhance the wear resistance and hardness properties and operating condition optimization for minimum material loss could be found.

Furthermore, there have been numerous studies conducted on the use of graphite lubricants and other solid lubricants in metal-forming processes. For instance, Frint et al. [1] showed that adequate lubrication in aluminum alloy metal-forming processes decreases friction force, increases the flowability of the material, and improves surface quality. In order to improve upon the properties of graphite lubricants, Podgornik et al. [2] studied the use of hexagonal boron nitride (h-BN), showing that h-BN offered similar properties in terms of friction force reduction while being superior in thermal stability and oxidation resistance. In the case of warm forging, Ngaile and Botz [10] tested graphite and boron nitride-silicone lubricants, showing that both lubricants had similar friction reduction capabilities but boron nitride was more thermally stable.

The most recent advancements are related to the usage of highly advanced lubricants and modeling approaches to enhance forming efficiency. Thus, Alimirzaloo et al. [7] studied the impact of nanolubricants CuO and Al_2O_3 in the forging process of aluminum alloys and discovered considerable decreases in surface roughness owing to the rolling and polishing action exerted by nanoparticles. The critical role played by graphite particles was proved by

Sugözü and Sugözü [8], who stated that smaller graphite particles offered reduced friction and better wear resistance, which was attributed to the more uniform distribution at the interface of contact. On the other hand, Poungprasert et al. [9] performed the modeling analysis of graphite lubricants applied in the hot forging process using the finite element method and showed that lubricant properties affected material flow, forging force, and temperature distribution significantly. Thus, the aforementioned research findings emphasize that not only reinforcement but also advanced lubrication are crucial in manufacturing.

3. Experimental Methodology

3.1 Material Selection

The material selected for the present research is Aluminium 6061, because of its high strength, ductility, good resistance against corrosion and ease of shaping. The starting material is cylindrical in shape with a diameter of 6 mm. The samples prepared had an aspect ratio h/d=1, since it is common practice in upset forging experiments to consider a constant aspect ratio.

3.2 Specimen Preparation

The aluminum rod was initially shaped using the Electrical Discharge Machining (EDM) process. Then the machined rods were further machined to make cylindrical samples with the same height of about 26-29 mm, depending on the desired aspect ratio. The EDM process used to shape the samples is described in Figure 1.

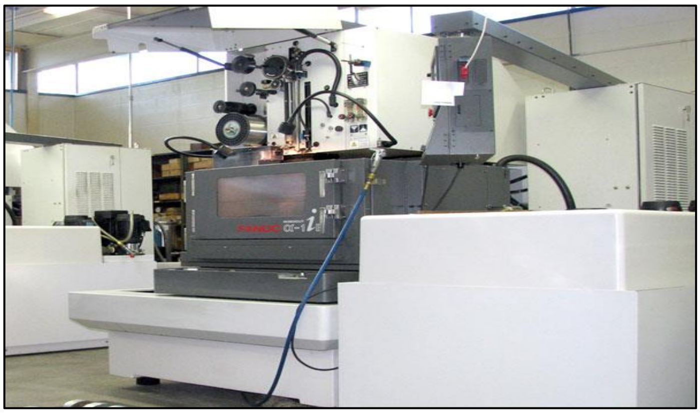

Figure 1. EDM Machining Process

Figure 1 illustrates the EDM technique utilized in making the Aluminum 6061 samples with exact dimensions and better surface finish. The EDM process helps achieve exact machining and reduced dimensional deviation and mechanical stresses. In addition, EDM ensures better machining of the samples thus reducing chances of surface defects and residual stresses that could affect the results of the experiments.

The experimental procedure starts with selecting raw aluminium rods that have consistent composition and no defects, making them useful for testing deformation. The selected aluminium rods are processed by machining to make fillet rods whose sizes and shapes are exact in order to prevent stress concentrations when testing the specimens. Further, the machined aluminium rods are cut into individual specimens with required height, using suitable cutting instruments. The prepared aluminium specimens ready for the tests are depicted in Figure 2. Finally, the surface cleaning of all specimens is conducted before experimentation to clean them from any contamination, such as oil, dust, or oxidation.

Figure 2. Prepared Aluminium Specimens

The specimens were machined to ensure a uniform aspect ratio, allowing identical dimensions of all specimens. Maintaining the same specimen dimensions reduces experimental variations enabling comparison of load-displacement behavior, barreling, surface roughness, and microstructure changes resulting from different lubrication conditions.

3.3 Lubrication Conditions

In order to investigate the influence of friction on the plastic deformation, the tests were performed using controlled parameters such as dry (un-lubricated) contact and the application of graphite powder lubricant with various particle sizes.

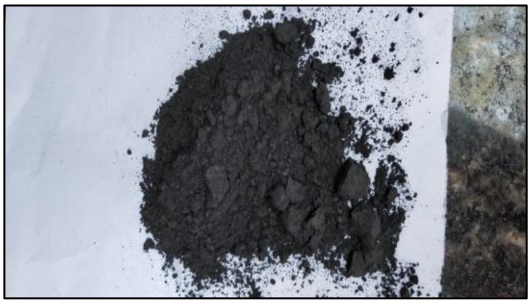

Figure 3. Graphite Powder Used as Lubricant

As seen from Figure 3, the graphite powder used for lubricating the specimens in the upsetting test. This powder has a layered crystal structure, which ensures low friction between adjacent particles due to their ability to slide over one another. It is important to mention that the lubricant was mixed with the mineral oil in order to increase the adhesion of the powder to the surface.the particle size of graphite powder considerably affects lubricating capacity, plasticity, and surface quality of materials. The lubricated specimens were covered by the mixture of the lubricant on both faces before starting the tests.

3.4 Experimental Setup

The upsetting tests were conducted using a compression testing machine with a maximum loading capability of 100 kN. The apparatus involves two rigid and flat platens, between which the specimen was placed with due care for its alignment. The loading process involved gradual application of the force in order to cause uniform deformation, while the displacement was recorded for analysis. Flat platens allow applying a homogeneous load and prevent bending of the sample. Load measurements are taken by means of a dial indicator, providing an exact reading of the force at all moments during the test, and the displacement is kept constant. The entire apparatus used for the compression test is shown in Figure 4.

Figure 4. Compression Testing Machine Setup

In this apparatus, rigid platens provide a controlled load of compressive nature to the cylindrical sample, while measuring the load and displacement. Appropriate alignment of the sample and platens provides a homogeneous loading of the sample without any bending.

3.5 Experimental Procedure

Each upset test experimental procedure was conducted in a systematic manner to minimize errors and ensure reproducibility of results. Firstly, specimen dimensions, both height and diameter, were accurately measured using the vernier calipers. If the test required lubrication, an appropriate lubricant was applied to the contact surfaces for analysis of friction. Specimen was aligned concentrically between the platens, and a gradual loading procedure was used until a 50% reduction in specimen height. Load and displacement data was gathered continuously during deformation of specimen. The specimen was extracted after deformation and analyzed based on such parameters as barreling, surface roughness, and microstructure of the specimen.

Figure 5. Specimen Before Compression

As can be seen from Figure 5, the Aluminium 6061 specimen is characterized by uniform cylinder geometry before being loaded into the test equipment. This condition represents the initial state of the specimen and serves as the basis for comparing its properties with those of the compressed specimens.

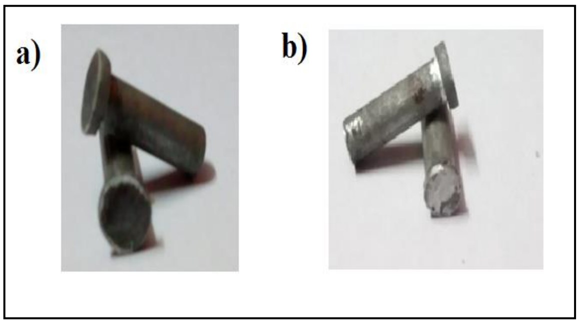

Figure 6. Specimen After Compression at (a) Dry Condition (b) Lubricated Condition

Figure 6 depicts the comparison of deformation behavior for Aluminium 6061 samples under lubricated and dry conditions following compression. The sample compressed in a dry state shows higher barreling owing to high friction forces that impede material flow near the contacting surfaces. On the other hand, the sample in a lubricated state shows uniform deformation with reduced barreling due to the low friction and enhanced material flow. This confirms the efficiency of graphite lubrication in improving forging results.

3.6 Measurement and Data Acquisition

3.6.1 Load–Displacement Data

The relationship between load and displacement was determined during the compression process by using the machine's data acquisition system. The collected data helped in investigating deformation behavior under different lubrication conditions.

3.6.2 Surface Roughness Measurement

To evaluate the effects of friction forces and deformation, the surface roughness analysis was performed for the samples. The parameters of Ra, Rq, and Rz were considered. Table 1 provides the numerical results obtained in this part.

Table 1. Surface Roughness of the Specimen After Compression at (a) Dry Condition (b) Lubricated Condition at Various Sizes

	Dry	**Size-1**	**Size-2**	**Size-3**	**Size-4**	**Size-5**
Ra	0.419	0.013	2.187	1.728	1.895	0.328
Rq	0.542	0.017	2.701	2.104	2.341	0.422
Rz	2.498	0.081	9.970	7.778	9.024	1.870

It is evident from the data that lubrication plays an important role in enhancing the surface integrity of the forged components. Of the different cases considered in the experiments, the smallest graphite particle size yielded the best roughness values, thus confirming the development of a lubricating layer that minimized the direct contact between the metals involved. This may not have been possible due to uneven distribution of particles at larger sizes leading to roughness.

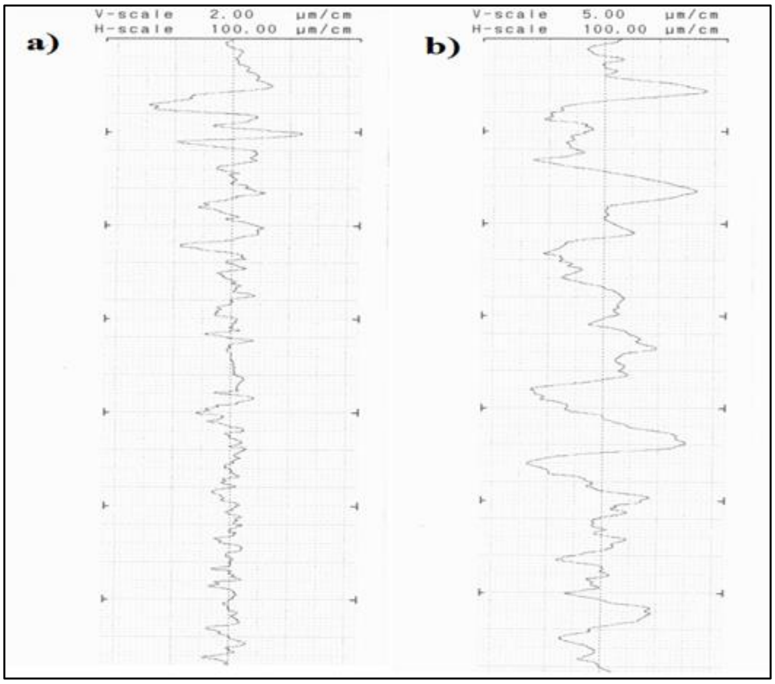

Figure 7. Surface Roughness Microstructure of the Specimen After Compression at (a) Dry Condition (b) Lubricated Condition

Figure 7 shows the roughness profiles of the samples after being subjected to compression in both dry and lubricated environments. It is evident that there are significant differences in the surface roughness caused by the variations in friction and lubrication. Surface roughness of the lubricated specimens is smoother because the adhesive wear is lower and the flow of materials is better.

3.6.3 Microstructural Analysis

Microstructural characterization was conducted through optical microscope and scanning electron microscope (SEM) analysis to study the grain flow and behavior of deformation prior to and after upsetting process. Samples from both undeformed and deformed state were cut, mounted, polished and etched appropriately to obtain clear images of the grain boundary. The microstructure of the undeformed sample is characterized by equiaxed grains, while the microstructure of the deformed samples consists of distorted grains oriented along the direction of flow, implying substantial plastic deformation. More distorted grains were seen at the edges due to the presence of friction effect leading to barreling. The grain structure was viewed using optical microscope, while the localized area of deformation or micro voids were observed using SEM.

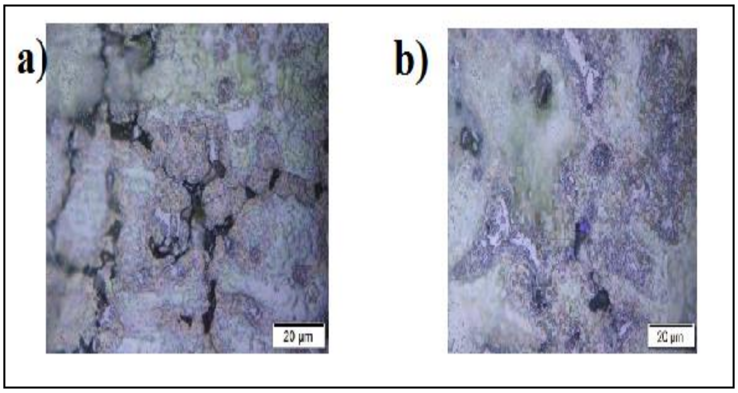

Figure 8. Microstructure of the Specimen After Compression at (a) Dry Condition (b) Lubricated Condition

Figure 8 shows microstructure analysis of the Aluminium 6061 sample after compressing under various lubrications. There is severe deformation, presence of localized bands of material deformation, and distorted grains observed in dry specimens as a result of high-friction limitations. Lubricated samples show uniform grain elongation and better deformation distribution, which indicate that there was better material flow in the upset process. Small-sized graphite particles facilitate uniform deformation, thus improving quality and performance of the forging.

3.7 Process Parameters Considered

This study involved consideration of some important factors to analyze the behavior of upset forging. Samples used for the experiment had an aspect ratio (h/d) of 1. Moreover, all experiments were done at a maximum height reduction of 50%. To assess the influence of friction during deformation process, two sets of frictional experiments were performed under different conditions, namely, dry and lubricated surfaces using graphite. In addition, varying sizes of graphite particles were used to assess their influence on friction limitation during deformation process.

3.8 Effect of Key Parameters

3.8.1 Effect of Temperature

While the tests in the study have been performed under conditions of cold working, it is also important to note that temperature has a huge impact on the process of deformation. The increase in the temperature makes the materials more ductile by increasing its capability of undergoing large amounts of deformation before breaking. It also reduces the amount of stress, meaning that there is less resistance to deformation. Moreover, temperature makes the metal easier to deform evenly and reduces the number of defects such as cracks or barreling.

3.8.2 Effect of Strain Rate

Strain rate is very important in determining how much impact it has on the flow stress and deformation of the material in upsetting process. With increased strain rate, there will be higher difficulty in the flow stress and deformation of the material because there will be less time for dislocation to move and dissipate the energy. Thus, with higher strain rates, there will be higher flow stress, which implies that higher loads have to be exerted on the materials.

3.9 Sample Size and Experimental Scope

Each test piece was subjected to one of the lubrication methods in the preliminary experiment. The purpose of the experiment was to study the effect of the particle sizes of graphite on upset behavior and the surface. While the experiment showed obvious distinctions between the lubrication methods, further experiments will be conducted to increase the reliability of the data.

The compression tests were performed in adherence with ASTM E9 guidelines to make sure that there is consistency in the experiment process. This ensures uniformity in the geometry of the specimens, ensuring that all specimens undergo uniform deformation during the test while the loading process remains consistent as well. Such reliability in experimental results is crucial for the analysis of the upsetting process.

4. Results and Discussion

4.1 Load–Displacement Behavior

Load vs displacement data for upsetting clearly indicated the influence of lubrication in controlling the process of deformation. For dry specimens, it was noted that higher loads were needed due to increased friction at the surface while for lubricated specimens, deformation was more easy and less forceful as compared to dry specimens. It was noticed from the experiment that among all the lubricant conditions, finest graphite particles showed better results regarding deformation and thus can be taken as most effective lubrication in the process.

4.2 Deformation Characteristics and Barreling

On visual inspection of the compressed specimens, it was noticed that lubrication had a great effect on barreling in upsetting. It was observed that due to higher friction at the interface, barreling was more prominent in the case of dry specimen. On the other hand, graphite lubricated specimens showed less barreling This reduction in barreling can be attributed to effective lubrication and hence lesser value of friction coefficient in the process. From all the lubricated conditions, the finest graphite particle showed the best results as far as uniform deformation was concerned.

4.3 Deflection Behavior

The displacement data collected from the compression tests reveal that the lubrication process had a considerable impact on the material deformability. In the absence of lubrication, the material became more resistant to deformations, thus having a smaller displacement value for an identical amount of load. On the other hand, in the case when the specimens were lubricated with graphite, the specimens demonstrated a higher deformation value when exposed to an equal load. The specimen with the smallest graphite particles proved to be the most effective one.

4.4 Surface Roughness Analysis

Out of all lubricating conditions, the largest percentage reduction in roughness was experienced for the size 1 graphite particles, with reductions of 96.90%, 96.86%, and 96.76% for Ra, Rq, and Rz, respectively. This means that an effective lubricating film was created which significantly reduced metal-on-metal contact during upsetting. Interestingly, medium-sized graphite particles (size 2, size 3 and size 4) provided a higher level of roughness than in the dry sample. This could possibly have been due to uneven particle distribution or insufficient lubrication film formation. However, the larger sized graphite particles (size 5) helped in achieving smoother surfaces with 21.72% reduction in Ra compared with the dry sample. This highlights the effect of particle size on lubrication efficiency in cold upsetting of aluminium 6061.

Table 2. Percentage Change in Surface Roughness Relative to Dry Condition

Condition	Ra (µm)	Reduction in Ra (%)	Rq (µm)	Reduction in Rq (%)	Rz (µm)	Reduction in Rz (%)
Dry	0.419	0	0.542	0	2.498	0
Size-1	0.013	96.90	0.017	96.86	0.081	96.76
Size-2	2.187	-421.96	2.701	-398.34	9.970	-299.12
Size-3	1.728	-312.41	2.104	-288.19	7.778	-211.37
Size-4	1.895	-352.27	2.341	-331.92	9.024	-261.25
Size-5	0.328	21.72	0.422	22.14	1.870	25.14

Table 2 presents the comparative study of the percentage change of surface roughness parameters with respect to the dry case for varying sizes of graphite particles. If the reduction is positive, it indicates a better surface finish, whereas negative reduction implies degradation of surface finish. From the results, it can be concluded that the Size-1 graphite particles have produced the maximum reduction in surface roughness values, which proves their excellent lubricating action.

4.5 Microstructural Analysis

Observations made using optical microscope on both dry and lubricated samples showed that there was notable difference in their deformation behavior. The dry sample showed extensive distortion in grains as well as deformation bands, which suggest non-uniform deformation behavior due to friction forces. On the other hand, graphite lubricated samples showed more uniform elongation of grains as well as better material flow behavior. This uniform deformation in graphite lubricated sample indicates how graphite improves the process of deformation through reduction in friction forces. Graphite particles with the finest size showed best uniform deformation.

From the above analysis, it can be concluded that friction dominates the behavior of material deformation in upset forging process. The use of graphite lubricant has been found to reduce the friction forces and hence reduces forming load, eliminates barreling, improves surface finish and makes deformation more uniform. Among various sizes of graphite particle, finest graphite showed best performance.

5. Conclusion

From the experiments, it is clear that the specific forming energy required for plastic deformation of the material is minimum when the lowest graphite powder particle size is used, moderate for the largest graphite particle size and maximum in case of dry (no lubricant) situation, thus emphasizing the significance of lubrication in minimizing the deformation resistance of materials. On the other hand, a comparative assessment of the surface roughness of the specimens in terms of graphite powder particle sizes in relation to the dry condition shows better surface roughness characteristics when fine graphite powder is used for lubrication purposes. Moreover, the results obtained through microstructural evaluation of the specimens by Optical Scanning Electron Microscope prior to and after upset forging show how the size of the graphite particle affects the microstructure and the nature of deformation resistance of the aluminium 6061 alloy samples. The use of graphite for lubrication purposes significantly reduces the deformation resistance of the aluminium 6061 alloy specimens.

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