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# The effect of processing parameters on the wear properties Al6061/GNP composites produced by hot pressing

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## Abstract

*In the present study, the effect of graphene nanoplatelet (GNP) reinforcement in Aluminum material at different rates was investigated on tribological properties. In this scope, the samples were produced by the hot press under determining different production parameters. The wear characteristics of the composites were determined using the ball-on disc wear test method. Ball on disc wear test showed that the Al6061/GNPs composite which was produced with the addition of 1 wt% GNPs, a sintering temperature of 600 °C, and a sintering time of 45 min, had the best wear resistance. Thanks to the GNPs reinforcement, a 61 % reduction in wear rate was achieved when compared to the non-reinforced Al material. The effects of the production parameters on the friction coefficient were investigated using the Taguchi method and it was determined that the most important parameter affecting the friction coefficients of the composites was the wt % GNPs addition. The results showed that the addition of GNPs is an important reinforcing material that reduces the wear rate when added to the structure at certain rates.*

***Keywords:*** *Aluminum, graphene nanoplatelet, composite, wear.*

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# Sıcak presleme yoluyla üretilen Al6061/GNP kompozitlerin aşınma özelliklerine üretim parametrelerinin etkisi


## Öz

*Bu çalışmada, alüminyum farklı oranlarda grafen nano plaka (GNP) ile takviyelerindirilerek elde edilen kompozit malzemenin tribolojik özellikleri incelenmiştir. Bu kapsamda, numuneler sıcak pres cihazında belirlenmiş olan parametreler altında üretilmiştir. Kompozitlerin aşınma karakteristikleri ball on disk aşınma test metodu kullanılarak belirlenmiştir. Ball on disk test sonuçları ağırlıkça %1 oranında GNP içeren, 600 °C sinterlenen, 45 dakika süresince sinterlenen Al6061/GNPs kopozitlerin en iyi aşınma direncine sahip olduğunu göstermiştir. GNP takviyesi sayesinde, takviyelendirilmemiş Al malzemesiyle kıyaslandığında aşınma oranında %61 azalma elde edilmiştir. Sürtünme katsayısı üzerinde üretim parametrelerinin etkisi Taguchi yöntemi ile araştırılmıştır ve kompozitlerin sürtünme katsayısı üzerinde en etkin parametrenin ağırlıkça GNP oranının olduğu belirlenmiştir. GNP'nin yapıya belli oranlarda eklendiğinde aşınma oranını azaltan önemli bir takviye malzemesi olduğunu sonuçlar göstermiştir.*


***Anahtar kelimeler:*** *Alüminyum, grafen nano plaka, kompozit, aşınma.*

## 1. Introduction

Metal matrix composites have received great attention in many areas in recent years thanks to their reinforcement materials. Generally, micro-sized reinforcements have been used as the reinforcement phase, especially in recent years, the use of nano-sized reinforcements has been increasing [1]–[3]. In addition to ceramic-based reinforcements such as $B_4C$, SiC, WC, and TiC; Carbon-based nano reinforcements such as graphene, and carbon nanotubes have overcome specific requirements [4].

Graphene reinforced composites have high electrical and thermal conductivity as well as high mechanical properties such as 0.5-1 TPa elastic modulus and about 130 GPa tensile strength. Such high mechanical properties are an advantage of being in a two-dimensional (2D) structure [5]. Thanks to such attractive properties, graphene reinforcement has gained popularity in composite production, especially metal and ceramic matrix composite. Metal matrix composites are most widely used in aerospace, automotive and biomedical fields. It has exceptional properties, especially in areas that require lightweight [6].

Nanocomposites have difficulty in production due to the agglomeration tendency of nano reinforcements in the matrix phase. Although this difficulty has been partly eliminated by the ball milling process in previous studies, studies on production variety, the reinforcement volume fraction, and production parameters have continued in the composite processing field [7]. Conducting the ball milling process at optimum levels has directly affected the mechanical properties of the produced composites. Thanks to ball milling, clustering of nano reinforcements and possibly unwanted reactions could be prevented [8].

Aluminum matrix metal composites (MMC) have been produced by different methods. Subbaiah et al. [9] produced graphene nano-platelets reinforced composites with Pure Aluminum (Al) matrix using stir casting method followed by cold working. GNPs content ranges from 0.50 to 2 wt%. Maximum mechanical properties were obtained in 0.5 wt% GNPs reinforced composite with 88.39 MPa tensile strength and 56.08 HV. In addition, it has been reported that the number of voids increased with increasing weight percent reinforcement, resulting in a decrease in ductility and it has been stated that the dispersion process is important in the production of nano-reinforced composites. It has been determined that there are some drawbacks to the nano reinforcement mixing process in the stir casting method.

Xia et al. [10] produced graphene nanoplatelets reinforced composites, Al 7075 alloy as matrix phase, by spark plasma sintering method. It has been reported that Graphene nanoplate reinforcement refines the grain size and the mechanical properties in composites and increases the hardness and elasticity modulus values by 29% and 36%, compared to the matrix material. Prashantha Kumar et al. [11] studied fatigue and wear properties of Al 6061 and Al 6061-Graphene composite (0.2, 0.4, 0.6 wt% Graphene). Ball milled powders were first cold compacted under 450 MPa pressure and then sintered at 500 °C in an inert gas atmosphere. The fatigue life cycle decreases as the graphene content increases, and it is found to be less than the Al6061 matrix alone, primarily because it is more vulnerable to crack initiation by pores.

As mentioned above; The properties expected from composite materials can change depending on the realization of production methods at optimum parameters. As a result of production processes that cannot be performed under optimum conditions, metal matrix composites may encounter undesirable consequences such as porosity, excessive grain growth, and microcrack structures. It is also known that aluminum material has a serious inclination in production processes due to its lightness and low wear resistance. Therefore, it is of great importance to obtain the optimum values of the production parameters for wear characteristics.

This study aims to examine the effect of production parameters and graphene reinforcement percentages on the wear properties of Al composites. For this purpose, Al6061-GNP composites were produced by the powder metallurgy method. The experimental results were analyzed with Taguchi and the effects of factors (wt% Graphene, processing temperature, and processing time) on wear resistance were compared.

## 2. Materials and methods

In this study, raw composite powders with different reinforcement ratios were used. 99% pure (average particle size 40 micron) Al6061 powder was preferred as the matrix phase, 1-2 wt % GNPs with 99% purity (5 nm size) as the reinforcement phase. In Figure 1, scanning electron microscope (SEM) images of the powders used in the study are given.

After the specified matrix and reinforcement powders were mixed in certain proportions, ball milling was performed for 250 rpm and 1 hour. The ball powder ratio is 10: 1. Ball material alumina balls were used. The mechanically alloyed composite powders were then consolidated in one step. Composite samples were produced in an inert gas atmosphere under a 50 MPa load using a hot press. Production parameters were designed through L8 orthogonal design. In Table 1, production parameters are given depending on % wt value, sintering temperature, and sintering time.

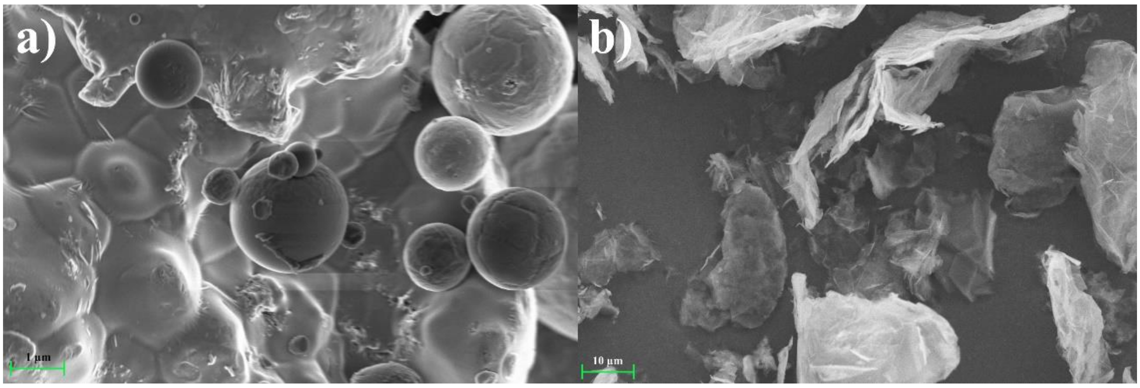


Figure 1. Raw powders a) Al6061 b) GNP

Specific metallographic processes have been applied to hot-pressed composites before the ball-on disc wear test. First of all, all samples were sanded up to 1200 grade with SiC paper and then polished. After metallographic processes, the samples were weighed on a precision scale. To investigate the tribological properties of nanocomposites, dry sliding wear tests were conducted using the CSM Instruments Tribometer in a ball-on disc at room temperature. A stainless steel ball (diameter: 6mm) was used as the abrasive. Wear characteristics of composites were evaluated under 2 N applied load and 250 m sliding distance conditions. Besides, dry sliding wear tests were conducted at room temperature and relative humidity to 50% for each sample.

Table 1. Production parameters

| | Temperature (°C) | Time (min.) | wt% Grafen |
|---|---|---|---|
| Level 1 | 500 | 30 | 1 |
| Level 2 | 600 | 45 | 2 |

## 3. Results and discussion

Pin-on Disc wear test was applied to examine the wear characteristics of the produced composites. At the end of the test, the wear losses, wear rates and friction coefficients of the samples were determined. Equations 1 and 2 are used for the calculation of the exceedance rate. The volume of worn composite (ΔV) was calculated beforehand. The volume of worn composite(ΔV) varies depending on the ratio of weight loss (Δm) and material density (ρ).

$$\Delta V = \frac{\Delta_m}{\rho} \tag{1}$$

The calculated volume of worn composite (ΔV) value was formulated together with F applied load and sliding distance (L), and WR (wear rate) was calculated.

$$WR = \frac{\Delta_V}{(P \times L)} \quad (2)$$

As a result of obtained from, it was determined that wt.% GNP is the most important parameter affecting the wear resistance of the composites. It was determined that the wear resistance of composites at certain production parameters could be increased when the matrix material was compared with aluminum. It is thought that the self-lubricant property of the reinforcement phase graphene caused a decrease in these wear losses. Due to the high surface area of graphene and high van der Waals forces in nano-sized, it may lead to agglomeration. As a result, it has been stated in previous studies that partial deterioration in the structure and local micro-cracks may occur.

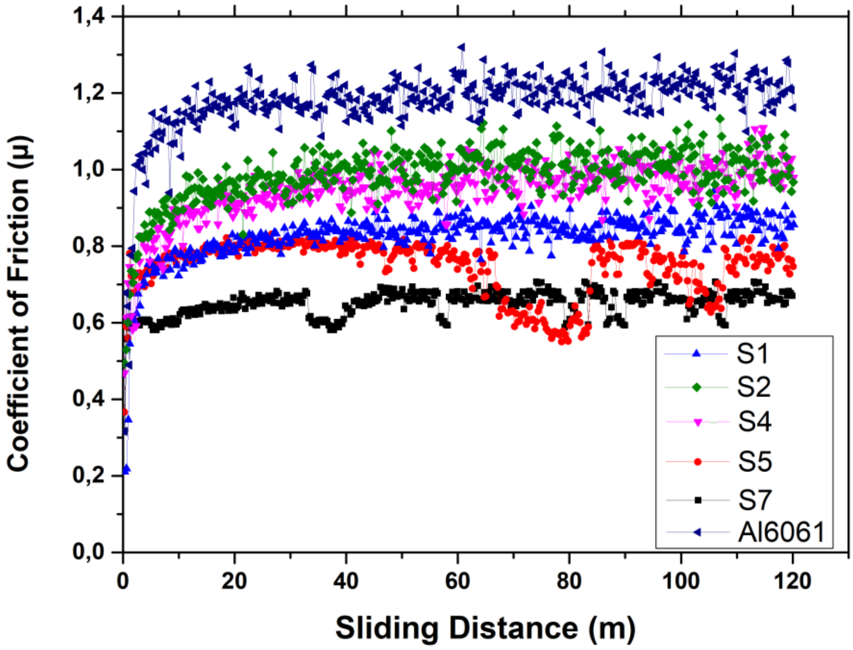


Figure 2. The variation of friction coefficient in produced samples

In the wear results, it was determined that there was a decrease in the wear resistance with the increase of the percent by weight graphene. This is based on the agglomeration tendencies of nano-sized reinforcements. The wear characteristics of Al/MWCNT were also affected by sintering temperature. The highest wear resistance was achieved at a sintering temperature of 500°C. The improvement in wear resistance was reduced as the sintering temperature was increased to 600°C due to microstructural coarsening. In Table 2, the wear rates of the samples are shown depending on the production parameters.

$$\frac{S}{N} Ratio = -10log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (3)$$

Table 2. The variation of wear rate Al6061/GNPs samples

| **Sample** | **Temperature** | **Duration** | **wt% Grafen** | **Wear rate** |
|---|---|---|---|---|
| | °C | min | | $((mm^3/(N.m))$ |
| S1 | 500 | 30 | 1 | $8,2672x10^{-6}$ |
| S2 | 500 | 30 | 2 | $25x10^{-6}$ |
| S3 | 500 | 45 | 1 | $7,93651x10^{-6}$ |
| S4 | 500 | 45 | 2 | $19x10^{-6}$ |
| S5 | 600 | 30 | 1 | $7,60582x10^{-6}$ |
| S6 | 600 | 30 | 2 | $13,6667x10^{-6}$ |
| S7 | 600 | 45 | 1 | $6,94444x10^{-6}$ |
| S8 | 600 | 45 | 2 | $18,3333x10^{-6}$ |

In Figure 2, the friction coefficient values of the samples produced in the study, for which minimum, maximum and average friction coefficient results were obtained, are given. It was determined that the friction coefficient values were compatible with the wear rates. Minimum friction coefficient values of 0.625 μ and 0.745 μ were obtained from samples coded S7 (Sintering Temperature: 600 °C, Sintering duration: 45 min., wt.% Grafen:1) and S5(Sintering Temperature: 600 °C, Sintering duration: 30 min., wt.% Grafen:1), respectively. The average friction coefficient value (0.825 μ) was determined from the sample numbered S1 (Sintering Temperature: 500 °C, Sintering duration: 30 min., wt.% Grafen:1). The maximum friction coefficient values were obtained from the S4 (Sintering Temperature: 500 °C, Sintering duration: 45 min., wt.% Grafen:2) and S2 (Sintering Temperature: 500 °C, Sintering duration: 30 min., wt.% Grafen:2) coded samples as 0.946 μ and 0.985 μ. The friction coefficient value of 1.1788 μ was determined for the non-reinforced aluminum material.

In Figure 3, wear images of unreinforced aluminum material and reinforced composites after wear are given. In Figure 3.a, the presence of deep cavity structures in monolithic aluminum material is clearly seen. Due to the soft structure of the unreinforced Al material, it has been observed that regional crack formations occur in the structure under the effect of the applied load during the wear test. It is thought that with this crack progression, weak areas in the structure grow and cause separations in the flake structure. Sintering temperature: 600 °C, Sintering duration: 45 min. containing 1 wt% Graphene reinforcement. In the composite sample produced under production conditions, there are also narrower abrasive lines as well as on the wear scar, there are also delaminated regions due to adhesion (Figure 3.c). When these formations were evaluated, it was determined that the wear mechanism was mix type. In composites containing 2 wt% reinforcement Graphene, on the other hand, it was determined that the addition of high GNPs created deep layers on the wear surface and regional cracks were formed (Figure 3.b). These damaged surfaces also coincide with increased wear rates. Lu et al[12]; suggested that the mass loss values in the material after the wear test were directly related to the wear resistance. It was determined that high GNPs supplementation reduced the wear resistance. He reported that this situation is compatible with the Archard model. The pressure on the wear surfaces is effectively transferred from the matrix phase to the carbon-based nano reinforcement. Since such reinforcements have the load-bearing capacity, they have an important role during wear [13], [14].

Mohammadi et al. determined in their molecular dynamics simulation studies that, because of the enhanced dislocation movement in the Al/Graphene coherent-like interfacial area, the plastic deformation in the front of the indenter is more severe for the Al/Graphene composite [15].

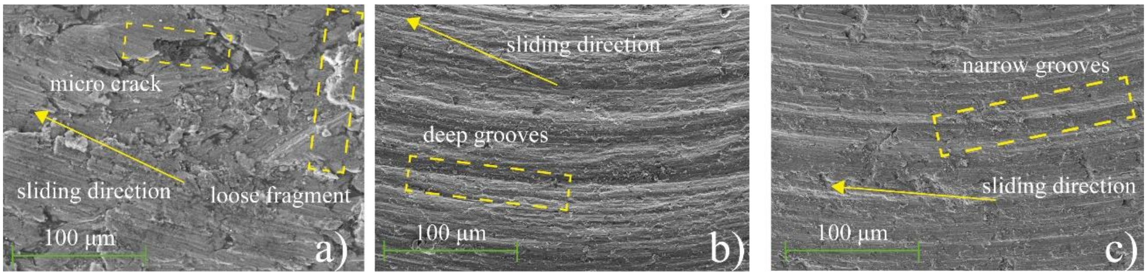


Figure 3. SEM images of the samples a) Unreinforced Al6061 material b) Al/GNPs Composite (2 wt%), c) Al/GNPs Composite (1 wt%)

In particular, it is clearly seen that 1% GNP reinforcement provides an improvement in wear properties. The above-mentioned evidence indicates that GNPs play an important role in improving wear performance. The worn surface evaluation was found to be in high reliable agreement with COF (Coefficient of Friction) and wear rate values.

The material with the maximum wear rate among the produced samples was obtained from sample 2 with a value of $25x10^{-6}$ $mm^3/Nm$. (Sintering temperature: 500 °C, Sintering duration: 30 min. 2 wt% GNPs), the minimum wear rate was obtained from sample 7 with a value of $6,94444x10^{-6}$ $mm^3/Nm$ (Sintering temperature: 600 °C, Sintering duration: 45 min. 1 wt% GNPs). When compared to the wear rate of Al material without reinforcement ($18x10^{-6}$ $mm^3/Nm$), it was determined that 61.6 % improvement was achieved in the wear rate with GNP reinforcement.

The above-mentioned positive effect of graphene nano reinforcement is in addition to the appropriate reinforcement dispersion in the reinforcement phase; load-transfer effect ($\sigma_{LT}$), grain growth restriction ($\sigma_{H-P}$); enhanced dislocation density due to thermal mismatch ($\sigma_{CTE}$); It has been reported that strengthening mechanisms such as and Orowan strengthening ($\sigma_{OR}$) have an effect. Particularly, nano-sized reinforcements characteristically limit grain growth because they pin grain boundary migration [16]. In other words, The grain boundary area increases as grain size decreases, acting as a pinning point and preventing additional dislocation movement. Eventually, with the reduction of this movement training, the initiation of plasticity in the material is also hindered [17-19].

In Figure 4, microstructures of composites containing 1 wt% and 2 wt% GNP are given. It was observed that increasing GNP reinforcement created regional aglomeration in the structure.

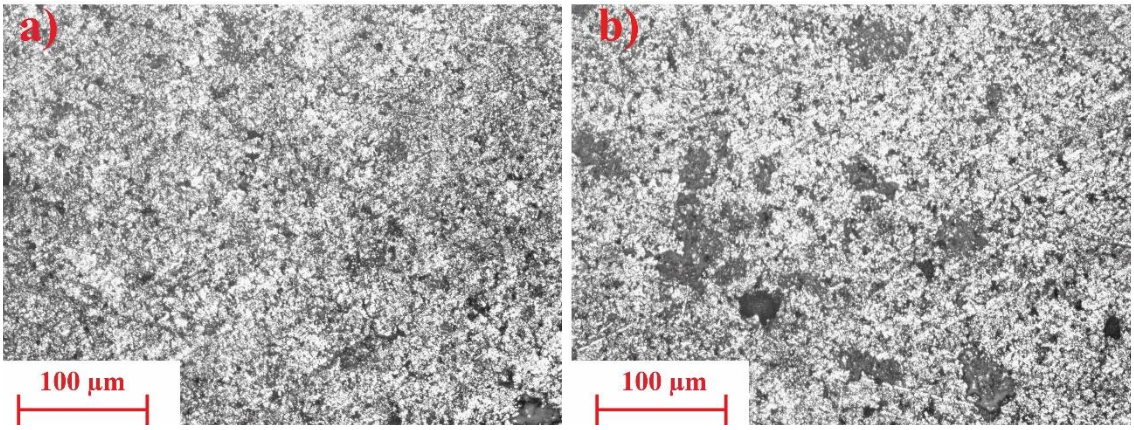


Figure 4. Composites with different GNP ratios a) 1 wt% GNP b) 2 wt%

In this study, since the output value (coefficient of friction) is wanted to be minimized, the smaller the better approach should be chosen by using Equation 3. The increase of graphene nano reinforcement in the composite structure causes severe agglomeration tendency. This undesirable situation also damages the transfer films at the friction interfaces and reduces the wear resistance. Another morphological consequence of this situation is the appearance of peeled debris on the wear surfaces that abrasive wear is shown by these symbols.

The optimum processing parameters of friction coefficient are determined to be sintering temperature: 600 °C, sintering duration: 45 min. 1 wt% GNPs. Table 3 shows the ranking of production parameters as well as the means of various parameters. According to the S/N ratio, the combination of parameters affecting the coefficient friction gives the optimum values (Figure 5). By evaluating the delta values in Table 3, the effects of production parameters on wear proporties were determined. The presence of high delta values indicates that the parameter has a significant impact on the outcome. As can be seen from Table 3, the graphene reinforcement ratio has the biggest effect on coefficient friction, while it is followed by processing temperature and duration factors, respectively.

Table 2. Response for S/N ratios of the Al6061/GNPs composites

| | **Factors** | | |
|---|---|---|---|
| **Level** | **Temperature (°C)** | **Duration (min)** | **wt% Grafen** |
| 1 | 1,0206 | 1,4173 | 2,5271 |
| 2 | 2,2306 | 1,8340 | 0,7242 |
| Delta | 1,2100 | 0,4167 | 1,8029 |
| Rank | 2 | 3 | 1 |

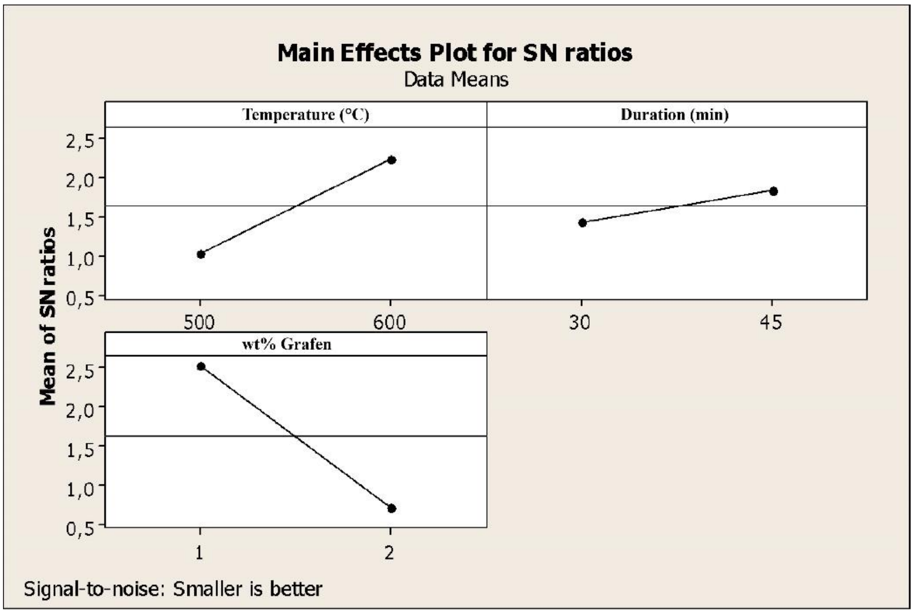


Figure 5. Main effects plots for S/N ratios

Figure 6 shows a probability plot, all of the points are clustered around the mean value, indicating that the designs chosen are appropriate.

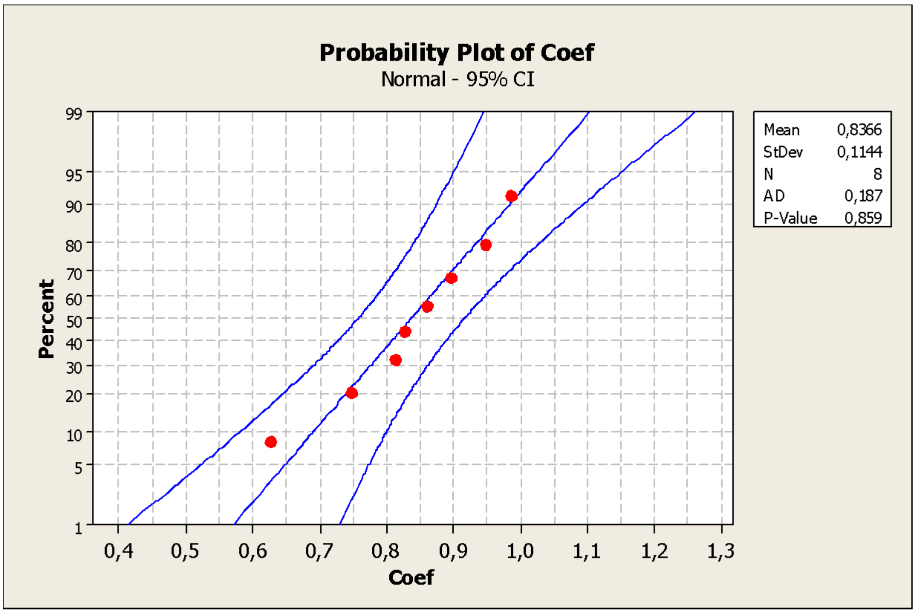


Figure 6. Probability plot of coefficient friction

It was seen that the hot pressing process at relatively high temperatures increases the wear resistance. It was determined that this parallel increase also resulted in positive effects in sintering times. However, as a result of the decrease in wear resistance with increasing GNP addition from 1% to 2%, it would be meaningful to limit the GNP addition to a maximum of 1%. It was determined as a result of the evaluation of the obtained findings that the production parameters were effective on the wear properties of Al6061/GNP composites. In the study, the effects of temperature, time and reinforcement ratio were evaluated, but it is thought that production pressure can also change the composite properties. It is also thought that the effects of production parameters can be investigated more comprehensively by increasing the number of experiments and using metaheuristic algorithms [20-22]. In addition to this situation; Although the constant wear test parameters were examined in the study, it was determined that the change of standard wear test parameters is also an area that can be examined in determining the wear properties of composites.

## 4. Conclusions

In this study, Al/GNPs (1-2 wt%) composites in different process parameters were successfully produced by the powder metallurgy method.

After the ball on disc wear test was performed at room temperature, the minimum wear rate (6,94444x$10^{-6}$ $mm^3$/(N.m)) was obtained from Sample 7 (Production parameters: sintering temperature: 600 °C, sintering duration: 45 min) 0.1 wt% GNPs). The minimum friction coefficient value was obtained from the same sample as 0.825 μ.

Compared to the unreinforced monolithic Al material, a 61.6 % decrease in wear rate was achieved among the specified production parameters.

It was determined by the Taguchi method that the greatest effect on the friction coefficient was wt% GNPs reinforcement, followed by sintering temperature and time, respectively.

It has been determined that there will be significant gains with the addition of graphene nanoplatelet reinforcement at low reinforcement rates in increasing the wear resistance of soft metals such as aluminum.

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