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# Optimizing Surface Quality of Al5080 Alloy via Nanoparticle-Enhanced Ball Burnishing: A Taguchi Approach

Süleyman Çınar ÇAĞAN[1*]

[1]*Department of Mechanical Engineering, Engineering Faculty, Mersin University, Mersin, Turkiye*
*Orcid: 0000-0002-5552-2135*

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***Anahtar Kelimeler***

*Al5080 alaşım*
*Nanopartikül ile geliştirilmiş yağlama*
*Bilyalı parlatma*
*Taguchi*
*Optimizasyon*

***Graphical/Tabular Abstract (Grafik Özet)***

*This study investigated the effect of burnishing on the surface quality of Al5080 aluminium alloy. By optimizing the force, feed rate, and Al nanoparticle concentration, surface roughness was reduced by 90%. / Bu çalışma, Al5080 alüminyum alaşımında parlatma işleminin yüzey kalitesine etkisini incelemiştir. Kuvvet, ilerleme hızı ve Al nanopartikül konsantrasyonu optimize edilerek yüzey pürüzlülüğü %90 oranında azaltılmıştır.*

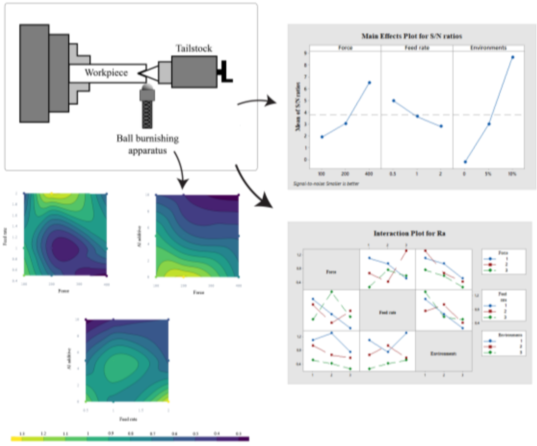


***Figure A**: Experimental setup and results /**Şekil A:** Deneysel düzenek ve sonuçlar*

***Highlights (Önemli noktalar)***

- *The surface quality of Al5080 alloy was improved by 90% with nanoparticle enhanced ball burnishing process. / Al5080 alaşımının yüzey kalitesi, nanopartikül destekli bilyalı parlatma işlemi ile %90 oranında iyileştirilmiştir*
- *The optimum process parameters were determined by using the Taguchi method. / Optimum işlem parametreleri, Taguchi yönteminin kullanılmasıyla belirlenmiştir*
- *The lowest surface roughness was obtained with 400N polishing force. / 400N parlatma kuvveti ile en düşük yüzey pürüzlülüğü elde edilmiştir.*
- *This method can be applied in the production of high performance aluminium parts used in sectors such as automotive, marine and aerospace. / Bu yöntem, otomotiv, denizcilik ve havacılık gibi sektörlerde kullanılan yüksek performanslı alüminyum parçaların üretiminde uygulanabilir.*

***Aim (Amaç):*** *To optimise the nanoparticle assisted ball burnishing process to improve the surface finish of Al5080 alloy. / Al5080 alaşımının yüzey kalitesini iyileştirmek için nanopartikül destekli bilyalı parlatma işlemini optimize etmek.*

***Originality (Özgünlük):*** *An innovative approach to improve the surface finish of Al5080 alloy using nanoparticle-enhanced lubricant is presented. / Nanopartiküllerle geliştirilmiş yağlayıcı kullanılarak, Al5080 alaşımının yüzey kalitesini iyileştiren yenilikçi bir yaklaşım sunulmuştur.*

***Results (Bulgular):*** *The surface roughness was improved by 90% using grease containing 10% aluminium nanoparticles, 400N force and 1 mm/min feed rate. / Yüzey pürüzlülüğü, %10 alüminyum nanopartikülü içeren gres yağı, 400N kuvvet ve 1 mm/dak ilerleme hızı ile %90 oranında iyileştirilmiştir.*

***Conclusion (Sonuç):*** *Nanoparticle assisted ball burnishing has proven to be an effective method for industrial applications by significantly improving the surface finish of Al5080 alloy. / Nanopartikül destekli bilyalı parlatma, Al5080 alaşımının yüzey kalitesini önemli ölçüde artırarak endüstriyel uygulamalar için etkili bir yöntem olduğunu kanıtlamıştır.*

*Corresponding author, e-mail: cinarcagan@mersin.edu.tr
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# Optimizing Surface Quality of Al5080 Alloy via Nanoparticle-Enhanced Ball Burnishing: A Taguchi Approach

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**Abstract**

This study investigates the impact of ball burnishing on the surface quality of Al5080 aluminum alloy, focusing on burnishing force, feed rate, and lubricant conditions. The primary objective of this research is to optimize the nanoparticle-enhanced ball burnishing process to improve the surface quality of Al5080 alloy, which is widely used in the marine, automotive, and aerospace industries. The research employs an innovative approach using grease with incorporated aluminum nanoparticles as a lubricant. Experiments were designed and analyzed using the Taguchi method, a statistical technique that uses orthogonal arrays to determine optimal process parameters with minimal experimental runs. A contact-based profilometer measured surface roughness parameters (Ra and Rz). The key parameters used in this study: burnishing force (100N, 200N, 400N), feed rate (0.5 mm/min, 1 mm/min, 2 mm/min), and aluminum nanoparticle concentration in the lubricant (0%, 5%, 10% by weight). Results indicate that surface finish improves with increasing burnishing force, moderate feed rates, and higher concentrations of aluminum nanoparticles in the lubricant. The optimum surface quality was achieved using a burnishing force of 400N, a feed rate of 1mm/min and a 10% concentration of aluminum nanoparticles in the lubricant, resulting in a 90% reduction in surface roughness compared to the untreated surface. This research contributes to enhancing knowledge of surface treatments applicable to Al5080 alloy, aiming to improve surface characteristics for high-quality aluminum products, particularly those used in marine and coastal environments. The findings have significant implications for industries requiring high-performance aluminum components with improved surface properties.

# Al5080 Alaşımının Yüzey Kalitesinin Nanopartikül Destekli Bilyalı Parlatma ile Optimize Edilmesi: Bir Taguchi Yaklaşımı

***Makale Bilgisi***

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**Öz**

Bu çalışma, bilyeli parlatmanın Al5080 alüminyum alaşımının yüzey kalitesi üzerindeki etkisini parlatma kuvveti, parlatma hızı ve yağlayıcı koşullarına odaklanarak araştırmaktadır. Bu araştırmanın temel amacı, denizcilik, otomotiv ve havacılık endüstrilerinde yaygın olarak kullanılan Al5080 alaşımının yüzey kalitesini iyileştirmek için nanoparçacıklarla geliştirilmiş bilyeli parlatma işlemini optimize etmektir. Araştırma, yağlayıcı olarak alüminyum nanopartiküller içeren gres yağı ortamı kullanarak yenilikçi bir yaklaşım kullanmaktadır. Deneyler, en az deneysel çalışma ile optimum işlem parametrelerini belirlemek için ortogonal dizileri kullanan istatistiksel bir teknik olan Taguchi yöntemi kullanılarak tasarlanmış ve analiz edilmiştir. Temas tabanlı bir profilometer yardımıyla yüzey pürüzlülük değerleri (Ra ve Rz) ölçmüştür. Bu çalışmada kullanılan temel parametreler: parlatma kuvveti (100N, 200N, 400N), parlatma hızı (0,5 mm/dak, 1 mm/dak, 2 mm/dak) ve yağlayıcıdaki alüminyum nanopartikül konsantrasyonu (ağırlıkça %0, %5, %10). Sonuçlar, yüzey kalitesi artan parlatma kuvveti, orta parlatma hızları ve yağlayıcıdaki daha yüksek alüminyum nanopartikül konsantrasyonları ile iyileştiğini göstermektedir. Optimum yüzey kalitesi: 400N parlatma kuvveti, 1mm/dk parlatma hızı ve yağlayıcının da %10 alüminyum nanopartikül katkılı gres yağı ortamında gerçekleştirilen deneylerde elde edilmiş ve işlenmemiş yüzeye kıyasla yüzey pürüzlülüğünde %90 azalma olduğu gözlemlenmektedir. Bu araştırma, özellikle deniz ve kıyı ortamlarında kullanılan alüminyum malzemeler olmak üzere yüksek kaliteli alüminyum ürünler için yüzey özelliklerini iyileştirmeyi amaçlayan Al5080 alaşımına uygulanabilir yüzey işlemleri hakkındaki bilginin artırılmasına katkıda bulunmaktadır. Bulgular, gelişmiş yüzey özelliklerine sahip yüksek performanslı alüminyum bileşenlere ihtiyaç duyan endüstriler için önemli çıkarımlara sahiptir.

*Corresponding author, e-mail: cinarcagan@mersin.edu.tr
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## 1. INTRODUCTION (GİRİŞ)

The Al5080 series has become relevant in several industries since it exhibits a high strength-to-weight ratio, corrosion resistance, and formability [1,2]. These alloys are widely used in aerospace, automotive, and marine industries, where surface finish is vital in controlling the performance of the parts and their life span [3,4]. Al5080 is widely acknowledged for its excellent weldability as well as excellent performance corrosion resistance in seawater, hence commonly used for marine and coastal services [5]. The Al5080 alloy is widely used in various industries due to its excellent combination of properties. The automotive sector uses Al5080 in the production of vehicle frames, body panels and structural components, taking advantage of its high strength-to-weight ratio to improve fuel efficiency [6]. The alloy is used in aircraft interiors and non-structural components [3].

The surface topographies in aluminum alloys affect their mechanical properties, wear resistance, and fatigue life [7, 8]. Improvement of the surface characteristics brings corresponding benefits, such as improved performance and extended useful life. According to the literature reviews, surface treatments can supposedly improve the mechanical properties and corrosion rate resistance of aluminum alloys [9, 10].

Among the methods for surface treatment, ball burnishing is one of the most significant methods used in industrial applications for better surface finish without affecting the material [11,12]. Ball burnishing is an operation employed as a cold working process that plastically deforms the surface layer of the material and allows the enhancement of the surface roughness and wear resistance [13,14]. This process has been demonstrated to improve the properties of a number of alloys, particularly aluminum alloys.

Recent advancements in nanotechnology have led to the exploration of nanoparticles as additives in lubricants to enhance their tribological properties [15,16]. This emerging field, often called nano lubrication, has shown significant potential in improving the performance of various lubricating systems [17,18]. Notably, the addition of aluminum (Al) nanoparticles to mineral oils has shown promising results in improving lubrication performance. Sharma et al. [19] demonstrated that Al nanoparticles dispersed in mineral oil significantly reduced friction and wear in sliding contacts. Similarly, Gu et al. [20] reported enhanced load-carrying capacity and anti-wear properties of lubricants containing Al nanoparticles.

Further research has supported these conclusions. According to Luo et al. [21], incorporating Al nanoparticles improves the extreme pressure property of lubricating oils. Similarly, Thampi et al. [22] found that adding Al nanoparticles increased the lubricants' thermal conductivity and viscosity index. The source of the improvements due to these nanoparticles has been attributed to the ability of the nanoparticles to form a protective tribofilm on the contacting surfaces, as explained by Gou et al. [23]. Furthermore, Peng et al. [24] showed that Al nanoparticles could act as nano-bearings that optimize friction in the boundary lubrication environment.

It is important to note that the benefits of nanoparticulate additives go beyond Al. For example, Padgurskas et al. [25] compared different metal nanoparticles and found that copper (Cu) and iron (Fe) nanoparticles also significantly improved the anti-wear properties of mineral oils. In addition, Zareh-Desari and Davoodi [26] investigated the synergistic effects of combining different nanoparticles and reported superior performance in hybrid nanolubricants containing both Al and Cu nanoparticles. However, the effects of ball burnishing on the Al5080 alloy, particularly concerning surface quality improvement, have yet to be extensively studied. While research has been conducted on other aluminum alloys [27,28], the specific behavior of Al5080 under ball burnishing conditions still needs to be explored.

The aim of this research is to investigate the effect of the ball burnishing process on the surface quality of Al5080 alloy. Unlike conventional methods, this study uses an Al nanoparticle-enhanced grease lubricant and investigates various force and feed rate parameters. This approach aims to exploit the ability of the nanoparticles to form tribofilms and act as nano-bearings, potentially improving process efficiency and reducing friction at the tool/workpiece interface. The study systematically varies critical process parameters, including burnishing force, feed rate, and the Al nanoparticle-enhanced grease oil environment, to optimize the ball burnishing process for this specific alloy. The effectiveness of the process will be evaluated through surface roughness measurements. Although previous research works have investigated the effects of ball burnishing on various aluminum alloys, the present work employs nanoparticle-enhanced lubricants as a coating for Al5080 alloy by ball burnishing process. Moreover, this work not only meets the demand of people in the study of surface treatment of Al5080 but also presents an effective method to improve the surface performance of aluminum alloys. By combining burnishing nanoparticles with some of the traditional burnishing processes and implementing the Taguchi optimization, this work has significantly contributed to developing new surface engineering techniques for high-performance aluminum parts.

This research aims to contribute to developing improved surface treatment techniques for aluminum alloys by investigating the relationship between ball burnishing parameters and the surface finish of Al5080 alloy. The findings of this study have potential implications for industries requiring high-performance aluminum components with improved surface properties, particularly in marine and coastal applications where Al5080 alloy is frequently used. Furthermore, the use of grease enhanced with Al nanoparticles provides insights into more efficient and environmentally friendly processing options for the surface treatment of aluminum alloys.

## 2.MATERIALS AND METHODS (MATERYAL VE METOD)

The Al 5080 alloy has a 2.65 g/cm³ density and a modulus of elasticity of 71 GPa. Its good formability, weldability, and corrosion resistance, particularly in marine environments, make it a preferred choice for applications in shipbuilding, marine structures, and other corrosive environments [29]. The alloy's strength can be further enhanced through work hardening, as it is a non-heat-treatable alloy. The surface roughness (Ra) of the unburnished Al 5080 alloy was measured to be 2.477 μm, providing a basis for surface improvement techniques. The Al5080 alloy examined in this study possesses a chemical composition (by weight percent) of 4.5% Mg, 0.7% Mn, 0.4% Fe, 0.2% Si, 0.1% Cu, and 0.25% Zn, with the remainder being Al.

The experiments were conducted using a conventional lathe machine. The schematic representation of the experimental setup is shown in Figure 1. The variations of the applied burnishing force were avoided by varying a test procedure along with the load cell. Particular emphasis was given so that no interference of any foreign particle comes in contact with the burnishing tool zone and the surface of the workpiece. This precaution was essential if any contamination was likely to occur at the interface, then the quality of the surface finish would be compromised.

The experimental design used the Taguchi method, which allowed for the systematic investigation of three key parameters: burnishing force, feed rate, and lubrication environment. The burnishing force was varied at three levels: 100N, 200N, and 400N. Similarly, three feed rates were examined: 0.5 mm/min, 1 mm/min, and 2 mm/min. For the lubrication environment, we explored using pure grease and grease enhanced with aluminum nanoparticles at two concentrations: 5% and 10% by weight.

The nanoparticle-enhanced lubricants were prepared by dispersing commercially available aluminum nanoparticles into base grease. Two concentrations were investigated: 5 and 10 wt.% of aluminum nanoparticles. The incorporation process here entails measuring the nanoparticles and mixing them with the base grease. Subsequently, the nanoparticles were dispersed and mixed thoroughly in the lubricant matrix to ensure that the nanoparticles were uniformly distributed throughout the lubricant matrix. This preparation method was used to test the impact of changing the nanoparticle concentration during ball burnishing on the surface finish performance of the Al5080 alloy.

This experimental setup allowed us to investigate the individual and combined effects of burnishing force, feed rate, and nanoparticle-enhanced lubrication on the surface quality of the Al5080 alloy specimens.

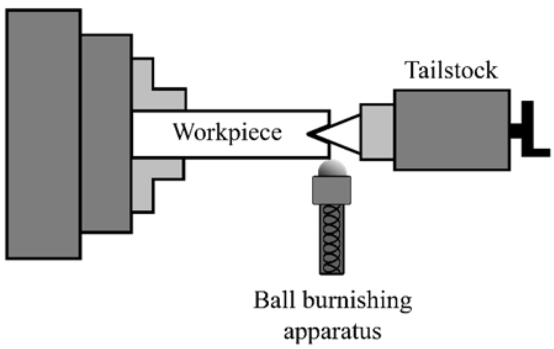


**Figure 1.** The schematic view of the experimental setup (Deney düzeneğinin şematik görünümü)

Optimizing experimental parameters is crucial for achieving desired outcomes while minimizing resource expenditure. For this purpose, the Taguchi method has become popular as an efficient approach for determining optimal parameter combinations with reduced experimental iterations [30]. This statistical technique employs orthogonal arrays and signal-to-noise (S/N) ratios to analyze the impact of various factors on process performance [31].

The Taguchi method offers three primary quality characteristics: "Nominal is best," "Smaller is better," and "Larger is better" [32]. These characteristics guide the interpretation of results based on the desired outcome. In our study, we adopted the "Smaller is better" approach for S/N ratio calculations, as our goal was to minimize surface roughness. The S/N ratio for this characteristic is calculated using the following equation:

$$S/N = -10\log\left(\frac{1}{N}\left(\sum_{i=1}^{n} Y_i^2\right)\right) \quad (1)$$

Where Yi represents individual surface roughness measurements, and n is the number of observations.

The experiment's design incorporated an L9 orthogonal array according to Taguchi's method. This enabled us to examine the three control factors at various levels. These are the factors to consider when it comes to burnishing force, feed rate, and the lubrication environment. This design allows searching over the parameters and finding the best optimum condition to produce low surface roughness.

Thus, in the achievement of the goal set, the focus was made on the following basic parameters, including burnishing force, feed rate, and lubrication environment by which the study sought to investigate their effects on the array of surface parameters of Al5080 alloy specimens (Table 1). The experimental design did not consider such interactions between main factors because it helps minimize their interference when the results are analyzed. In this regard, the S/N ratio was determined for every experimental run to measure the effect of the combination of parameters on Ra. The Taguchi method was employed in this study due to its robust experimental design approach, which facilitates the optimization of multiple parameters while minimizing experimental iterations and variability.

Apart from making the optimization more structured and efficient, this systematic approach also gives insight into the significance of individual factors that would be effective in attaining the preferred surface characteristics. The outcomes of this analysis will help develop subsequent contributions of ball burnishing to Al5080 alloy and other similar materials in industries.

**Table 1.** Process parameters and their limits (Proses parametreleri ve sınırları)

| Code | Factors | Levels | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| A | Force (N) | 100 | 200 | 400 |
| B | Feed rate (mm/min) | 0.5 | 1 | 2 |
| C | Environments | Pure | Grease oil containing 5% Al nano powder | Grease oil containing 10% Al nano powder |

Regarding surface quality, surface roughness is one of the most important characteristics used to define the nature and intensity of the surface. It is typically characterized by two components: optimal surface roughness, which depends mainly on the geometry of the cutting tool and feed rate per tooth, and inherent surface roughness, which occurs from various forms of process variability [33].

The arithmetic average roughness (Ra) is widely used as a standard measure of surface roughness [34]. It is defined as the sum of the absolute deviations of the profile from the mean line divided by the sampling length. Another parameter is the maximum profile height (Rz) average, which offers information about the highest peaks and pits inside the considered length [35]. The Ra value can be mathematically expressed as (Figure 2) [36]:

$$\mathrm{R_a} = \frac{1}{L}\int_0^L |y|\,dx = \frac{1}{L}\left(\sum S_{ui} + \sum S_{lj}\right) = \frac{S}{L} \tag{2}$$

$$R_a = R_t(S_u + S_l) \tag{3}$$

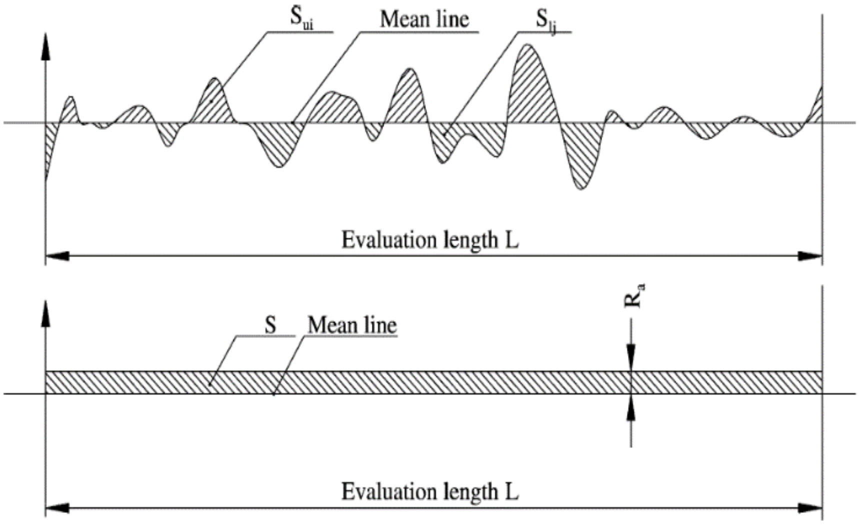


**Figure 2.** Schematic representation of surface roughness (Yüzey pürüzlülüğünün şematik gösterimi) [36]

In this study, surface roughness measurements were carried out using a Surftest SJ-210 (Mitutoyo) contact-based profilometer. The instrument has a diamond stylus with a 2 µm tip radius and a 60° detector type. Measurements were taken with a detector force of 0.75 mN, following the JIS'01 guideline. The cut-off length was set at 0.8 mm, with an evaluation length of 4 mm. The measurement speed was 0.75 mm/s and a Gaussian filter was applied. All measurements were made at an ambient temperature of 22.5 ± 1 °C. Seven measurements were taken at different locations on each sample to ensure repeatability, and the average Ra value was calculated.

## 3.RESULTS (BULGULAR)

Table 2 shows the surface roughness values obtained after subjecting Al 5080 aluminum alloy to ball burnishing processes under different parameters (force, feed rate, and % Al additive ratio). The resulting surface topography metrics are delineated for different burnishing conditions of the surface modification technique. The data reveal several significant trends which are consistent with the current literature in the field of surface engineering. Firstly, it was found that the force used during the burnishing operations tends to have an inverse relation with surface roughness. Thus, from the force range of 100 N up to 400, the overall Ra values decrease somewhat observantly, though with less impact in the case of the transition from 300 to 400, where the ratio decreases from 1. 102 µm to 0. 247 µm for the constant feed rate and keeping the additive constant at all times (experiment 1&7). This observation supports the findings stated by Loh and Tam [37] that increased force will lessen the roughness values because improved force does improve the flattening of surface asperities.

The overall surface quality and its relation with the feed rate present a more complex picture. As the result indicates, the feed rate does not affect performance consistently; it depends on other factors. In some experiments the increase in feed rate increases the Ra values as in Experiments 4 and 6 whereas in other experiments the value of Ra reduces as in Experiments 1 and 3. This variability agreed with the work of Capilla et al. [38] when they affirmed the presence of an optimal feed rate threshold in the operation of a CNC machine, and this threshold is affected by other factors.

The ratio of the aluminum additive also stands out to be highly impactful in enhancing the value of the surface finish. In general, an increase in Al-additives amounts leads to the decrease of Ra numerical value, as is the case with the transition from the first and even to the second digit. 102 µm in the pure state to 0 µm with focal lengths of 35, 50 and 70 mm. To obtain the maximum extent of oxidized silicon wafers, sintering was performed starting at 480°C and reaching about 504 µm with a 10% Al-additive (experiments 1 and 3). This trend endorses the works of Maximov et al. [39], who observed the positive impacts of lubrication in burnishing processes for aluminum alloys.

It is also important to note that the various parameters add up, affecting the results in a synergistic manner. The most negligible value of Ra (0. 247µm) was recorded for Experiment 7 and it was attained at the highest force of 400 N and the lowest feed rate of 0. 5mm/rev and the highest ratio of Al addition of 10%. This result further emphasizes the fact that in burnishing process optimization, parameter optimization plays a critical role, and many researchers, including Nguyen et al. [40], have carried out many research works in this aspect.

Lastly, Table 2 also represents the mutual influence between the process parameters. This fact was indicated by non-linear forms, which show that the impact of one variable cannot be discussed independently of others. This complexity is well explained in the studies conducted by Gomez-Gras et al. [41], which explained the interference of parameters while carrying out ball burnishing processes.

**Table 2.** Parameters and results after the burnishing process (Parlatma işleminden sonraki parametreler ve sonuçlar)

| Experiments | Parameters | | | Ra (µm) | Rz (µm) | S/N ratio |
|---|---|---|---|---|---|---|
| | Force | Feed rate | Environments Al additive ratio | | | |
| 1 | 100 | 0.5 | Pure | 1.102 | 4.839 | -0,8436 |
| 2 | 100 | 1 | %5 | 0.939 | 4.329 | 0,5467 |
| 3 | 100 | 2 | %10 | 0.504 | 2.933 | 5,9514 |
| 4 | 200 | 0.5 | %5 | 0.660 | 3.845 | 3,6091 |
| 5 | 200 | 1 | %10 | 0.405 | 2.188 | 7,8509 |
| 6 | 200 | 2 | Pure | 1.313 | 4.955 | -2,3653 |
| 7 | 400 | 0.5 | %10 | 0.247 | 1.459 | 12,1461 |
| 8 | 400 | 1 | Pure | 0.750 | 3.528 | 2,4988 |
| 9 | 400 | 2 | %5 | 0.577 | 3.071 | 4,7765 |

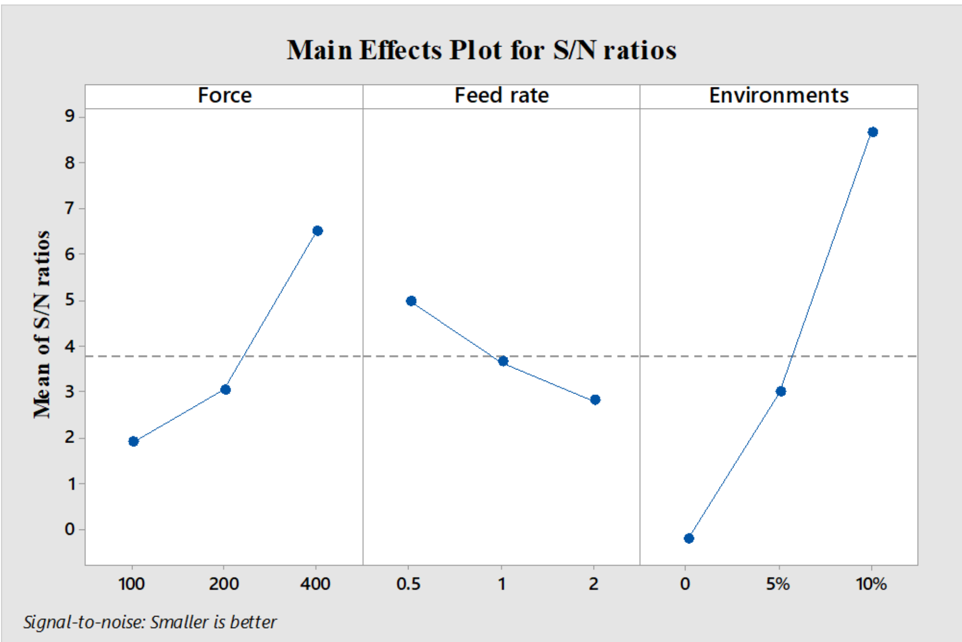


**Figure 3**. Taguchi's main effects plot for S/N ratios of Ra (Ra değerinin S/N oranları için Taguchi'nin ana etkiler grafiği)

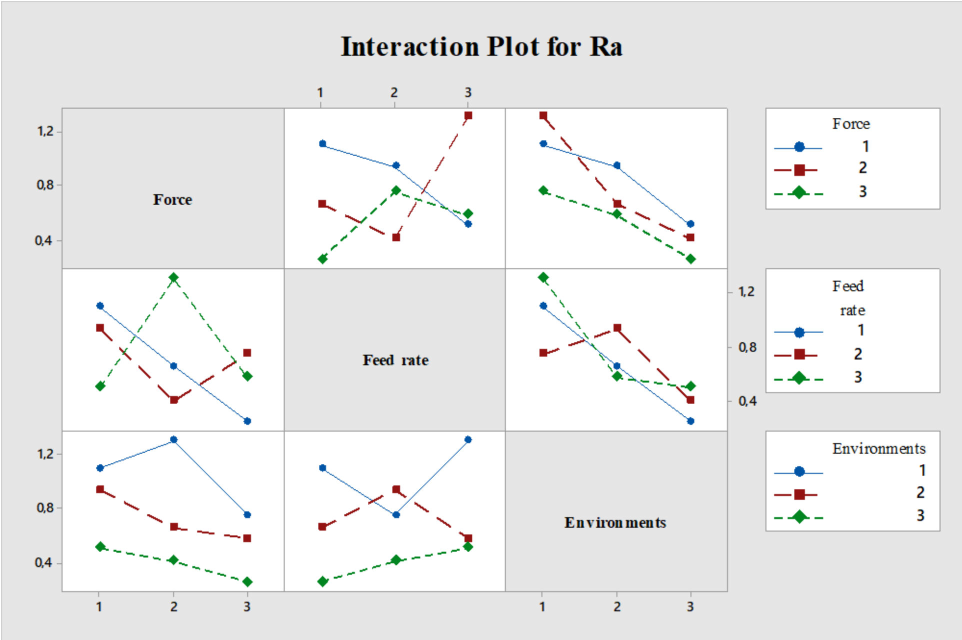


**Figure 4.** Interaction plot of parameters of Ra (Ra değerleri için parametrelerin etkileşim grafiğ)

The Taguchi main effects plot for Ra in Figure 3 demonstrates the influence of three critical parameters on the surface roughness of ball burnished Al 5080 alloy. The force parameter shows a robust negative correlation with Ra, indicating that increasing force significantly reduces surface roughness. The lowest Ra value is achieved at the highest force level (400 N). This finding is consistent with the work of Revankar et al. [42], who observed that higher burnishing forces led to improved surface finish in aluminum alloys due to enhanced plastic deformation of surface irregularities.

The feed rate exhibits a non-linear effect on Ra. As the feed rate increases from 0.5 mm/rev to 1 mm/rev, Ra decreases, but it increases again at higher feed rates. This suggests an optimal feed rate of around 1 mm/rev. El-Taweel and El-Axir [43] reported similar non-linear effects of feed rate in their study on ball burnishing of aluminum alloys, emphasizing the importance of identifying the optimal feed rate for each specific application.

The Al additive ratio shows a consistent negative correlation with Ra, with the lowest Ra value achieved at the highest Al additive ratio (10%). This effect can be attributed to the improved lubrication the aluminum additives provide during the burnishing process. Luca et al. [44] similarly found that appropriate lubrication in ball burnishing of aluminum alloys significantly improved surface quality.

Figure 4 presents an interaction plot of the parameters of Ra. In Taguchi analysis, a higher S/N ratio indicates a better quality characteristic (in this case, lower surface roughness). The S/N ratio plot provides additional insight into the robustness and consistency of each parameter's effect on Ra.

The force parameter shows a strong positive correlation with the S/N ratio, indicating that higher forces reduce Ra and lead to more consistent results. This aligns with the findings of Sequera et al. [45], who noted the importance of force in achieving reliable and consistent surface finish improvements in the burnishing of aluminum alloys.

The feed rate exhibits a non-linear relationship in the S/N ratio plot, as seen in the Ra plot, with the highest S/N ratio at around 1 mm/min. This reinforces the existence of an optimal feed rate and suggests that this rate also provides the most consistent results. Dorbane et al. [46] similarly observed the critical role of optimizing feed rate in achieving consistent surface quality in burnishing processes for aluminum alloys.

The Al additive ratio positively correlates with the S/N ratio, indicating that higher Al additive percentages reduce Ra and improve process consistency. This supports the findings of Rao et al. [47], who investigated the effects of lubricants on surface quality in burnishing processes and emphasized the importance of proper lubrication in achieving consistent and improved surface finish in metalworking operations.

These Taguchi analysis results, encompassing both the direct effects on Ra and the S/N ratio analysis, provide valuable insights for optimizing the ball burnishing process of Al 5080 alloy. They highlight the importance of considering both the magnitude of the effect on surface roughness and the consistency of the results when selecting process parameters.

In the process of the surface quality outcome, force and feed rate are vital factors affecting surface qualities. When the burnishing force is higher, the plastic deformation of surfaces of contact asperities is more effective, and the feed rate can be increased without a tremendous negative impact on the surface. However, feed rates have more significance when using lower forces and even lower rates are required for adequate surface finishing activities. The force also has a strong correlation with the Al nanoparticle concentration. Higher burnishing forces cause higher temperatures at the tool-workpiece interface, improving the formation of the continuous layer of Al nanoparticles that form the tribofilm.

It is also relevant how these feed rates contribute to Al nanoparticle concentration in the final product. At lower feed rates, the nanoparticles acquire a better opportunity to create an effective tribofilm as well as seal the surface topography. While the feed rate increases, it is also noted that the extent of improvement in surface finish by the use of nanoparticles may reduce if the concentration of the nanoparticles is not sufficient enough to render a strong tribofilm consistently. Such interactions demonstrate the interdependence of all factors that must be varied in the optimization process. The collective influence of all these parameters was found to be responsible for the enhanced surface characteristics noticed in the Al5080 alloy after the nanoparticle-aided ball burnishing operation.

The contour plots in Figure 5 provide valuable insights into the complex relationships between force, feed rate, and Al additive ratio on the surface roughness (Ra) of ball burnished Al 5080 alloy. As the force increases from 100 N to 400 N, a general trend toward lower Ra values is observed, particularly evident in the Force vs. Feed rate plot. This aligns with findings by Jerez-Mesa et al. [48], who reported that higher ball burnishing forces produce smoother surfaces due to more effective plastic deformation of surface asperities. The impact of feed rate, however, is not uniform across the force range. At lower forces, increasing feed rate tends to increase Ra, while this effect is less pronounced at higher forces. Travieso-Rodriguez et al. [49] also observed this non-linear relationship and emphasized the importance of optimizing feed rate in conjunction with other parameters. Higher Al additive ratios generally correspond to lower Ra values, especially at higher forces, as visible in the Force vs. Al additive plot. The lubricating effect of aluminum additives in improving surface finish is consistent with the work of Amdouni et al. [50], who studied the impact of lubricants on burnishing processes.

The contour plots reveal significant interactions between parameters, with the optimal combination of force and feed rate shifting with changes in the Al additive ratio. This complex interplay is reminiscent of findings by Gomez-Gras et al. [51], who emphasized the need for multi-parameter optimization in burnishing processes. The darkest regions in the plots, indicating the lowest Ra values, suggest an optimal processing window occurring at high force (300-400 N), moderate feed rate (0.8-1.2 mm/min), and high Al additive ratio (8-10%). Similar optimal processing windows have been identified in other studies, such as that by Maximov et al. [52], highlighting the importance of parameter optimization in achieving the best surface finish. In conclusion, these contour plots underscore the need for careful consideration of multiple parameters to achieve optimal surface finish in ball burnishing of Al 5080 alloy, a widely recognized principle in advanced manufacturing processes [53]. This comprehensive analysis of parameter interactions provides crucial guidance for optimizing the ball burnishing process, potentially leading to improved surface quality and performance of the processed Al 5080 alloy components.

The optimum parameter combination identified in this study, comprising a burnishing force of 400N, a feed rate of 0.5 mm/min, and a 10% concentration of aluminum nanoparticles in the lubricant, has significant industrial implications. This optimized process can be directly applied in manufacturing environments to improve the surface quality of Al5080 components used in the marine, aerospace and automotive industries. The improved surface finish achieved by this process can potentially lead to increased wear resistance, improved fatigue life and improved corrosion resistance of Al5080 parts, which is particularly important for components exposed to harsh environmental conditions. Consequently, this could lead to extended component life, reduced maintenance costs and improved overall performance of products made from this alloy. The use of nanoparticle-enhanced lubricants in the burnishing process not only improves surface quality but also opens up new opportunities for environmentally friendly and efficient surface treatment technologies in the manufacture of lightweight materials. In addition, the low feed rate of 0.5mm/min, while potentially increasing the machining time, ensures a high-quality finish that could justify the additional production time in high-value applications where surface quality is essential.

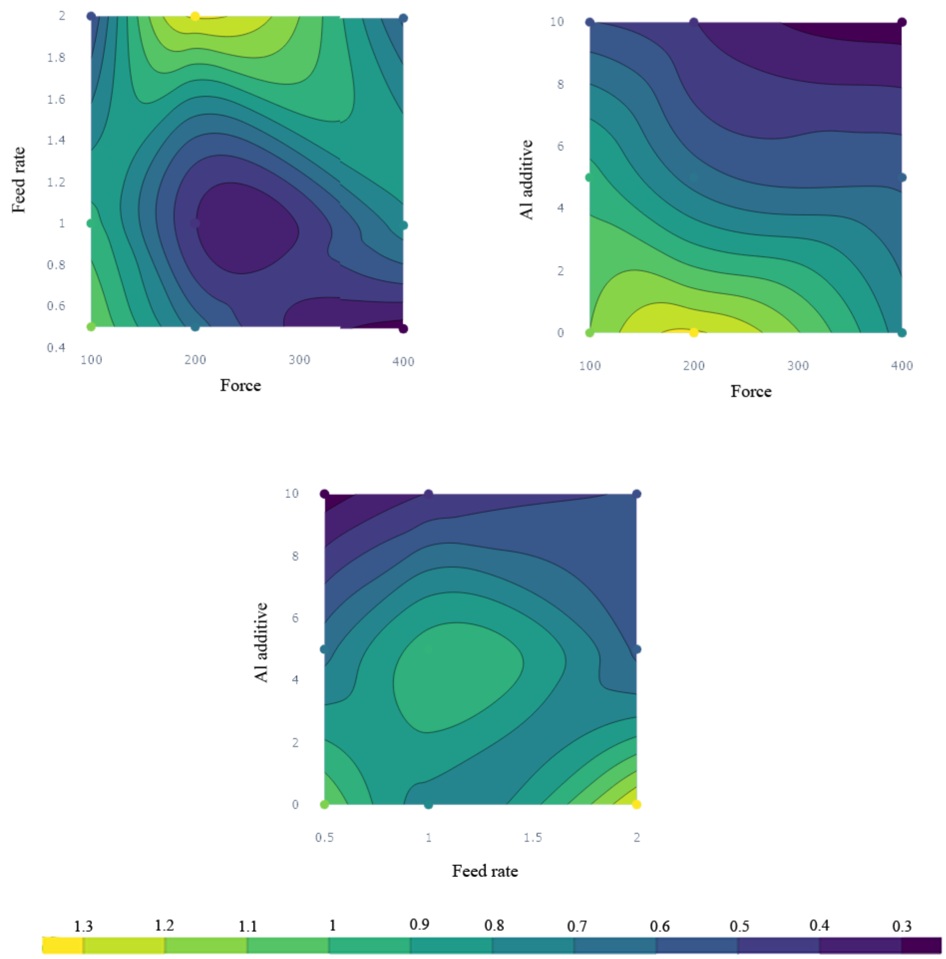


**Figure 5.** Contour plots of surface roughness (Ra) as a function of Force, Feed rate, and Al additive ratio for ball burnished Al 5080 alloy. (Parlatılmış Al 5080 alaşımı için Kuvvetin, İlerleme hızının ve Al katkı oranının bir fonksiyonu olarak yüzey pürüzlülüğünün (Ra) kontur grafikleri.)

## 4.CONCLUSIONS (SONUÇLAR)

It is evident that the ball burnishing process creates a higher level of conflict in enhancing the surface quality of Al5080 aluminum alloy. Key findings include:

From the results it can also be concluded that burnishing force has a negative relationship with relative surface roughness, in the sense that higher level of burnishing force produces low relative surface roughness.

Feed rate seems to have a non-linear relationship meaning that the best feed rate to use is around 0.5 mm/min. It could be ascertained that the incorporation of Al nanoparticles to the lubricating grease enhances surface finish effectively, and this increases as the concentration of the nanoparticles increases.

It is also seen that the relationship among the parameters is highly interlinked and therefore, the process optimization efforts call for a simultaneous, integrated, and comprehensive study of the factors influencing the operation.

The best values were achieved at high force of 400N, the feed rate of 0.5 mm/min, and at the highest ratio of the Al additive of 10%.

This study is useful for producers of Al5080 alloy and industries that apply this material, especially in situations where a high-quality surface finish is wanted. With the help of nanoparticle enhanced lubricants novel green and efficient surface treatment technologies has become possible.

The findings of this study have significant implications for various industries utilizing Al5080 alloy. In the marine industry, the optimized ball burnishing process has the benefit of increasing the corrosion resistance and life of marine parts, which in turn reduces maintenance costs. The aerospace industry can be a clear beneficiary of improved surface finishes, resulting in better aerodynamic performance and, therefore, better fuel economy. In automotive applications, improved wear resistance combined with smoothness can lead to a more durable and lightweight system.

The use of nanoparticle-enriched lubricants is a step towards greener manufacturing processes; therefore, costs can be reduced with a reduction in environmental impact. Such an approach could encourage new research into environmentally sustainable technologies in the manufacture of light alloys. The improved parameters provide a roadmap for surface improvement processes in the other aluminum alloys, which may change the surface treatment methods in the metal forming industries.

Further research should be directed towards evaluating the more durable performance of the existing treatment on this material, and also towards evaluating other types of Al alloys. As high-performance materials and the need for improved surface properties increase, the techniques demonstrated in this study could be useful in meeting the expanding requirements of the industry. This work fits within the broader category of surface engineering and developments in the manufacture of lightweight materials.

## DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

## AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Süleyman Çınar ÇAĞAN*:** He conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

## CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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