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Numerical and Experimental Investigation of Nano-Particle-Added Waste Oils on Lubrication Performance

Nano-Partikül Takviyeli Atık Yağların Yağlama Performansının Sayısal ve Deneysel Olarak İncelenmesi

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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF NANO-PARTICLE-ADDED WASTE OILS ON LUBRICATION PERFORMANCE

ABSTRACT

Metal forming is the shaping of metals by methods such as forging, extrusion, and rolling. The friction between the mold and the workpiece during metal forming is crucial in terms of the material's internal structure and surface quality. It is important to investigate and control this friction at the interface. In this study, the effects of vegetable oil, motor oil, nano oil and dry conditions on the coefficient of friction were investigated by ring compression test. For the preparation of nano-oil, silicon oxide was added to the waste vegetable oil at additive rates of 1%, 3%, and 5% by weight. The mixture was mixed first mechanically and then in the ultrasonic disperser. The rings are compressed in a hydraulic press machine (under 32 MPa pressure). The lubricating performance of the lubricants was determined on the Male and Cockroft friction calibration curves according to the size changes of the compressed rings. The highest coefficient of friction was found in the dry ring, and the lowest coefficient of friction was found in the 5% nano oily ring. The friction coefficient of the ring lubricated with 5% nano oil is 93.7% lower than in dry conditions. Afterward, the test was modeled axisymmetrically with the Abaqus/Standard finite element program. Due to the gradual loading of the force during pressing, deformation differences were detected between the simulation and experimental results. Since the deformation of the ring becomes more difficult with the increase of the friction coefficient, the barreling in the outer diameter has increased. As a result, the use of lubricants with low coefficient of friction during forming accelerates the process and reduces the deformation force.

Keywords: Friction, Lubricant, Ring Compression Test, Waste Oil.

Highlights

- Determination of friction coefficient of different lubricants by ring compression test
- Effect of SiO_2 nanoparticle reinforcement ratio on lubricating properties
- Modeling of the ring compression test with the Abaqus/Standard finite element program
- Comparison of deformations in experimental and simulation results
- Determination of the stress distribution of the compressed ring and its relationship with the friction coefficient

NANO-PARTİKÜL TAKVİYELİ ATIK YAĞLARIN YAĞLAMA PERFORMANSININ SAYISAL VE DENEYSEL OLARAK İNCELENMESİ

ÖZ

Metal şekillendirme, metallerin dövme, ekstrüzyon ve haddeleme gibi yöntemlerle şekillendirilmesidir. Metal şekillendirme sırasında kalıp ile iş parçası arasındaki sürtünme, malzemenin iç yapısı ve yüzey kalitesi açısından önemlidir. Bu çalışmada bitkisel yağ, motor yağı, nano yağ ve kuru koşulların sürtünme katsayısı üzerindeki etkileri halka sıkıştırma testi ile incelenmiştir. Nano yağın hazırlanması için atık bitkisel yağa ağırlıkça %1, %3 ve %5 oranında silisyum oksit ilave edilmiştir. Karışım önce mekanik olarak daha sonra ultrasonik dağıtıcıda karıştırılmıştır. Halkalar hidrolik pres makinesinde (32 MPa basınç altında) sıkıştırılmıştır. Yağlayıcıların yağlama performansı, sıkıştırılmış halkaların boyut değişikliklerine göre Male ve Cockroft sürtünme kalibrasyon eğrileri üzerinde belirlenmiştir. En yüksek sürtünme katsayısı kuru halkada, en düşük sürtünme katsayısı ise %5 nano yağlı halkada bulunmuştur. %5 nano yağ ile yağlanan halkanın sürtünme katsayısı kuru şartlara göre %93,7 daha düşüktür. Daha sonra test; Abaqus/Standart sonlu elemanlar programı ile eksenel simetrik olarak modellenmiştir. Presleme sırasında kuvvetin kademeli olarak yüklenmesi nedeniyle, simülasyon ve deneysel sonuçlar arasında deformasyon farklılıkları tespit edilmiştir. Sürtünme katsayısının artmasıyla halkanın deformasyonu zorlaştığı için dış çaptaki fıçılaşma artmıştır. Sonuç olarak şekillendirme sırasında düşük sürtünme katsayısına sahip yağlayıcıların kullanılması işlemi hızlandırır ve deformasyon kuvvetini azaltır.

Keywords: Sürtünme, Yağlayıcı, Halka Sıkıştırma Testi, Atık Yağ.

Highlights

- Halka sıkıştırma testi ile farklı yağlayıcıların sürtünme katsayısının belirlenmesi
- SiO2 nano-partikül takviye oranının yağlayıcı özelliklerine etkisi
- Abaqus/Standart sonlu elemanlar programı ile halka sıkıştırma testinin modellenmesi
- Deneysel ve simülasyon sonuçlardaki deformasyonun karşılaştırılması
- Sıkıştırılmış halkanın gerilme dağılımının ve sürtünme katsayısı ile ilişkisinin belirlenmesi

1. INTRODUCTION

Metal forming is the process of shaping sheet metals by bending or cutting. With metal forming, the sheets become durable and usable. During metal forming, contact occurs between the die and the workpiece. As a result of these contact events, friction forces occur. Friction significantly affects the quality of the product, production speed, and wear [1, 2]. For this reason, it is necessary to determine the friction conditions at certain limits. However, it is complicated to determine the friction conditions between the die and the workpiece. Because the friction magnitude changes depending on the location and time in the contact area [3].

Many methods (ring compression, double cup extrusion, barrel compression test, etc.) have been developed to simulate friction during forming [4]. The ring compression test is the most commonly used of these methods. With this test, the lubrication properties of different lubricants can be determined under friction conditions. The method is based on the size variation of the compressed rings. Because these changes create sensitivity to friction in the contact area [5]. If the material flows inward when the ring is compressed, the inner diameter becomes smaller and the friction increases. If the material flows outward, the inner diameter becomes larger and the friction decreases. Using these size changes, the friction coefficient is determined by the friction coefficient calibration curve developed by Male and Cockroft, shown in Figure 1 [6].

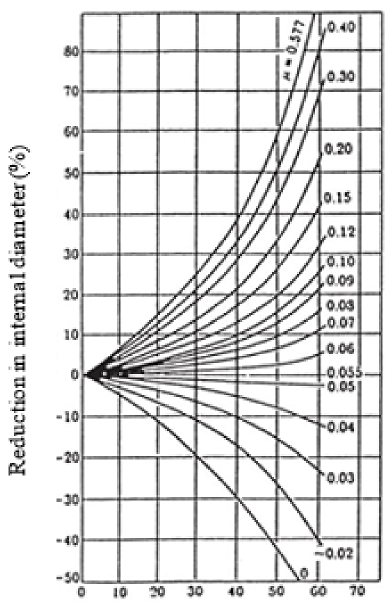

Figure 1. Friction calibration curves [6]

There are many studies on the determination of lubricant properties and comparing friction coefficients of different oils [6-26]. Sofuoglu and Rasty investigated whether the coefficient of friction curves used with ring compression tests are valid for all materials and test conditions [6]. As a result of the tests, it has been determined that using the general friction coefficient calibration curve for each material is incorrect. It is recommended to use calibration curves created according to test conditions and material to determine the coefficient of friction. Valero et al. determined the differences in the calibration curves under different load and lubricant conditions applied during the ring compression test [7]. They used two methods: lubrication at the beginning of compression (continuous) and the end of each compression (incremental). As a result, they suggested using the incremental method if the lubricant layer will remain constant, and the continuous method if the lubricant layer will not remain constant. Ma et al. developed a new method for determining the friction coefficient of magnesium (Mg) alloy sheets [8]. The bulging test is applied to the sheet metal processing with a hole in the center. It has been determined that the friction coefficient between the punch/piece can be calculated by increasing the hole diameter. Pang and Ngaile developed a new method to disperse SiO2 nanoparticles into the oil [9]. The distribution and tribological properties of the oil were investigated by dynamic laser scattering and ring compression tests. The dispersion process based on hydrodynamic cavitation is quite effective. It has been determined that the lubricating properties of nano-oils are increased by decreasing the particle size and increasing the dispersion time. Rajesh and Sivaprakash applied the ring compression test to aluminum rings in dry, graphite, zinc stearate, and MoS2 conditions [10]. The friction coefficients of the lubricants were determined according to the size change of the rings. The lowest coefficient of friction was determined in MoS2, Zinc stearate, and the highest coefficient of friction was determined in dry conditions. Li et al. investigated the friction behavior of A5 lubricant depending on the temperature and strain rate with the ring compression test [11]. The tests were carried out at strain rates between 0.05-15 s-1 and temperatures between 750-1000ºC. It was found that the coefficient of friction decreased with increasing temperature. It has been stated that the increase in the strain rate has an effect at temperatures above 950ºC and causes a decrease in the friction coefficient. Zhang et al. performed ring compression tests on Al5052 rings under different oils (hydraulic oil and MoS2 oil) and different loading speeds (0.15, 1.5, and 15 mm/s) [12]. As a result of the tests, it was determined that the friction coefficient decreased with the increase in loading speed. It has been detected that only the friction size depends on the loading speed in MoS2 oil, but both the friction size and the deformation threshold depend on the loading speed in hydraulic oil. Robinson et al. performed ring compression tests using physical modeling and the finite element method (FEM) [13]. Pure petrolatum, vaseline (V), zinc stearate (Z), talcum powder, and a mixture of vaseline-zinc stearate in different proportions were used as lubricants. After the tests, finite element modeling was used to obtain friction calibration curves, and determine geometrical variations and load-displacement results. The lowest coefficient of friction (0.07) was obtained in the V75%-Z25% mixture. The friction coefficient of other lubricants is from small to large; pure petrolatum (0.075), V50%-Z50% (0.08), V25% - Z75% (0.17), zinc stearate (0.22) and talcum powder (0.3). Keshtiban et al. used the ring compression test to determine the lubricating properties of some vegetable oils (olive oil, sesame oil, peanut oil, walnut oil, and wheat germ oil) and to compare them with mineral-based oil [14]. Al2024 rings were preferred for this test. Vegetable oils have a lower coefficient of friction than mineral-based oils. In addition, the required deformation force in vegetable lubricants has decreased as friction has reduced. The lowest coefficient of friction (0.340) was found in walnut oil. Keshtiban et al. investigated their constructive properties by adding SiO_2 at different rates (0.5%, 1%, 1.5%, %2 by weight) to different oils (peanut and walnut oil) [15]. AA2024 rings were used for the ring compression test, and the surface roughness of the rings was examined after the test. For comparison, different oils (MoS_2, zinc stearate, and SAE W10) were chosen as references. The friction coefficient of vegetable oils with 2% SiO_2 added is 40-48% less than powder lubricants (MoS_2 and zinc stearate) and 79-81% less than SAE W10. In addition, the highest surface roughness was determined in powder lubricants, and the lowest surface roughness was determined in 2% SiO_2 added walnut oil. Harikrisha et al. performed a ring compression test on the AA2014-T6 ring using three different lubricants (soap, boric acid, and vaseline) [16]. The friction coefficients of the lubricants were determined, and the hardness of the rings was examined. The lowest coefficient of friction (boric acid) was obtained in soap, and the highest coefficient of friction was obtained in petroleum jelly. It has been determined that the barrel effect significantly affects the ring hardness. The hardness value increases when the inner diameter is narrowed and decreases when it expands. Cristino et al. investigated the effect of roughness between surfaces and the oxide film formed by the effect of the environment on the friction coefficient during metal deformation [17]. They carried out this examination with the ring compression test. Compression test was applied to pure lead rings with AISI 316L steel discs with different surface roughness (0.04, 0.1, 0.2, 0.3, 0.5, 0.75 µm) under different environmental conditions (inert argon, air, and active oxygen). The friction coefficient was determined the highest in active oxygen and the lowest in argon gas. It is stated that the friction coefficient decreases with the increase of the surface roughness and is not affected by the amount of oxide layer. Li et al. applied compression tests to Incoloy 800H and Inconel 690 nickel alloy rings at different temperatures (1050, 1100, 1150°C) and different strain rates (0.01, 0.1, 1 s^{-1}) [18]. They preferred glass oils A5 and up68/2886. In the ring test results of Incoloy 800H with A5 lubricant (at strain rates of 0.1 and 1 s^{-1}), the friction factor decreased as the temperature increased. In the test with Up68/2886 oil, the friction factor increased as the temperature increased at all speeds. The lowest coefficient of friction (0.13) in A5 lubricant was obtained at 1150°C and strain rate of

1 s-1. The lowest coefficient of friction (0.11) in Up68/2886 lubricant was determined at a temperature of 1050°C and a strain rate of 1 s-1. Shahriari et al. investigated the effect of hot pressure on friction with different lubricants (graphite powder, glass powder, mica plate) on the Nimonic 115 superalloy ring [19]. 1100 and 1175ºC were preferred as test temperatures. According to test results, approximate coefficients of friction from lowest to highest; are mica plate (0.3), glass powder (0.35), graphite (0.55), and dry (0.69). In all lubricants, the friction coefficient increased with increasing temperature, but the least increase was determined for the mica plate. The temperature did not have much effect on this lubricant. Rudkins et al. performed the ring compression test under hot forming conditions [20]. They used medium carbon and lead-free steel rings for testing. They were tested in a 3000 kN hydraulic press in dry conditions at different temperatures (800, 900, 1000°C). As a result of the experiment, the friction coefficient increased with the increase in temperature, and there was no significant difference between the ring materials. Asai et al. investigated the effect of strain rate on the frictional behavior of graphite and non-graphite lubricants by ring compression test [21]. 0.45% carbon steel rings were increased by 5°C per minute to temperatures of 1000°C. The mechanical press was used for high-speed compression (38 mm/s), and the hydraulic press was used for low-speed (1.3 mm/s) compression. In the mechanical press tests, graphite and non-graphite lubricants showed a close friction effect, and low friction coefficients were measured. In the hydraulic press, a higher coefficient of friction was determined in non-graphite lubricants.The friction coefficient decreased as the amount of graphite lubricants decreased and the amount of non-graphite lubricant increased. In addition, it has been observed that non-graphite lubricants retain their lubricating properties in heat treatments under 450°C.

In this study, a compression test was applied to the rings of dry, motor oil, vegetable oil, and nano oils (1, 3, 5) in different ratios. Al6351 was chosen as the ring material. As a result of the tests, the friction coefficients of these six conditions were detected according to the size change. The experimentally determined friction coefficients were entered into the Abaqus/standard finite element program, and the test was simulated. The inner diameter change of the ring was determined according to the simulation results and compared with the experimental results.

2. MATERIAL AND METHODS

2. 1. Material

This study used motor oil, vegetable oil, and silicon oxide (SiO2) nanoparticles with oleic acid added vegetable oil. These materials are readily available and cost effective. SiO2 nanoparticles are low-cost, resistant to high temperatures, and easy to process. It is used in metal forming processes to improve tribological properties.

Due to the rolling motion of SiO2 nanoparticles during contact, the friction coefficient decreases, and the lubrication performance increases. For this reason, SiO2 nanoparticles are combined with other materials and used as a lubricant [27]. Oleic acid is a colorless, transparent, and odorless unsaturated fatty acid. Oleic acid is used in many areas, such as humectant, solvent, lubricant, and softener. This study uses it as a surfactant, reducing surface tension. Thus, it allows the materials to mix with each other better. The general properties of the materials used are given in Table 1.

Table 1. General properties of materials

Material Name	General Properties	Purpose of Usage
Vegetable Oil	It is a type of oil obtained from plants. The most important plants used in their production are soy, canola, olives and peanuts.	They are used in food and for cooking purposes.
Motor Oil	It is a fluid used to reduce heat and wear caused by friction.	It is used to lubricate, clean and protect the parts inside the engine.
Silicon Oxide	It is a transparent or translucent, hard and brittle inorganic substance. It is a fine white powder consisting of silicon oxide particles with a diameter of 10-30 nm. It is divided into two structural types, porous P-type silica and spherical S-type silica.	It is generally used for thickening and strengthening.
Oleic Acid	It is a fatty acid naturally found in various animal and vegetable oils. It is odorless and colorless. Oleic acid is the most common monounsaturated fatty acid in nature.	It is used as an ingredient in soaps and foods. It is also used as a solvent.

Many of the aluminum alloys are used in engineering applications, aerospace, automotive, manufacturing. Compared to other aluminum series, the 6000 series has features such as easy formability, high strength and corrosion resistance. Magnesium (Mg) and silicon (Si) are available as basic alloying elements in the 6000 series. This alloy series has a high hardenability by heat treatment. Al6351 is one of the most important alloys among the 6000 series. In this study, Al6351 was preferred because of its high hardness (95 BHN), low density (2.8 g/cm3) and advanced tribological properties. However, the tribological system is the most critical factor in the metal forming processes of Al6351. Different lubricants are used to improve this tribological system and reduce the friction between the surface and the workpiece. The chemical composition of Al 6351 is given in Table 2 and its mechanical properties are given in Table 3 [28, 29].

Table 2. Chemical composition of Al 6351

Element	Ti	Cu	Fe	Mg	Zn	Si	Mn	Others	Al
Wt%	0.2	0.1	0.5	0.4	0.2	0.7	0.4	0.15	97.35

Table 3. Mechanical properties of Al6351

Property	Value
Poisson's ratio, ν	0.3
Yield strength, σ_Y (MPa)	222.65
Elasticity modulus, E (MPa)	70000
Strength Coefficient, K (MPa)	808.37
Hardening Exponent, n	0.48

The aluminum rings used in the ring compression test are in a geometric ratio of 6:3:2. The Al6351 rings have an outer diameter of 15.30 mm, an inner diameter of 7.60 mm, and a height of 5.12 mm (Figure 2).

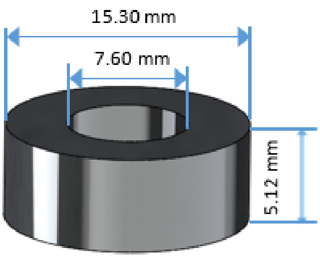

Figure 2. Aluminum alloy rings

With the compression test, engineering stress-engineering strain data are obtained. However, the true stress-true strain data of aluminum are required in the program. For this, the true stress-true strain diagram of aluminum was drawn with Equation 1 and Equation 2.

$$\sigma_t = \sigma_e(1 + \varepsilon_e) \qquad (1)$$

$$\varepsilon_t = ln(1 + \varepsilon_e) \qquad (2)$$

In Equation 1, σ_t is the true stress, σ_e is the engineering stress and ε_e is the engineering strain. In Equation 2, ε_t is the true strain. The true stress-true strain diagram shown in Figure 3 was drawn with the results of the compression test on the Al6351 rings.

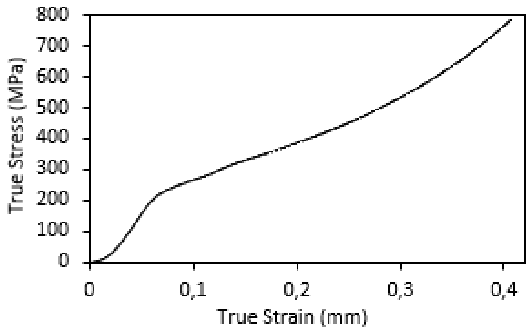

Figure 3. True stress-true strain diagram of Al6351

2.2. Methods

2.2.1. Experiment Of The Ring Compression Test

The most commonly used method to determine the coefficient of friction nowadays is the Ring compression test. This method is based on the principle of compressing the ring samples between two plates. The friction coefficient is determined from the friction calibration curve in the direction of the compressed rings inner diameter and height change [6].

In this study, compression tests were performed on Al6351 rings under different conditions. Firstly, nano-oils were prepared for the compression test. Nano oils preparation method and the ring compression test are illustrated in Figure 3. 100 ml of waste oil and different weight ratios (1, 3, and 5%) of silicon oxide were mixed mechanically for 5 minutes. Oleic acid (0.5% by weight) used as a surfactant was added to the mixture and mixed in an ultrasonic disperser for 15 minutes. Then, dry and immersed rings in different oils (vegetable oil, motor oil and nano oil) were compressed in a press machine (under 32 MPa pressure). Percent changes in the inner diameter and height of the compressed rings were calculated. Finally, the friction coefficients of the oils were determined from the Male and Cockroft friction calibration curves.

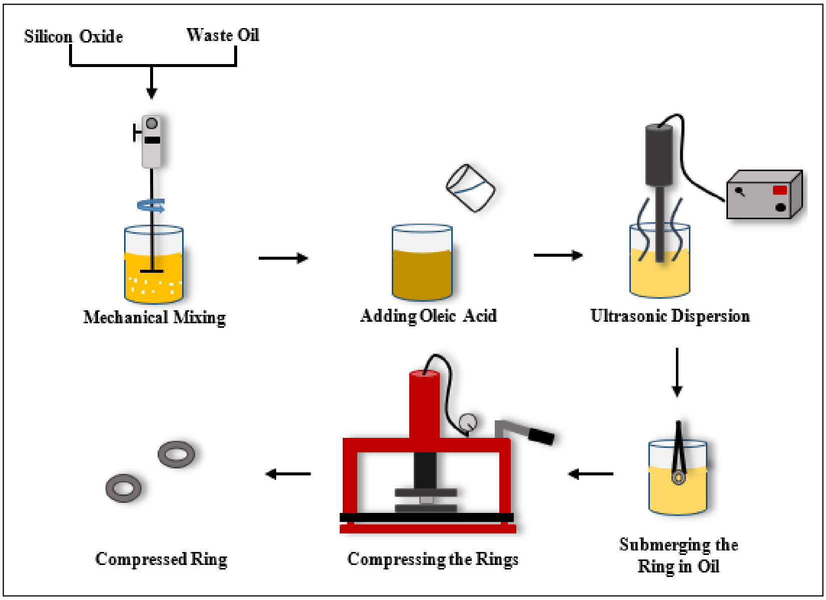

Figure 3. Nano oil preperation method and the ring compression test

2.2.2. Simulation Of Ring Compression Test By FEM

After the experiment, the ring compression test was modeled in the Abaqus/Standard finite element program. The test is modeled with element type CAX4R (4-point axisymmetric) and symmetrical about the x-axis. Due to its axisymmetric nature and the presence of two axes of symmetry in each plane, the ring is constructed as a 2D model with a one-quarter representation. The purpose of modeling the ring axisymmetrically is to complete the analysis of the model in a shorter time. Ring and plate surfaces are modeled as axisymmetric deformable and axisymmetric analytical rigid, respectively. The upper and lateral surfaces of the ring are defined as interfaces, since their surfaces will contact the plate when the ring is compressed between two plates. The friction coefficients obtained from the experiment were entered into the program. The simulation is modeled to end when the ring height decreases by 50%. The rings have meshed the same size (0.1 mm) for all coefficients of friction (Figure 4).

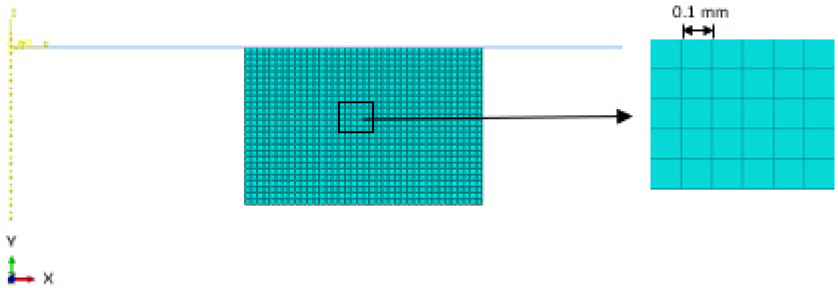

Figure 4. 0.1 size mesh ring

3. RESULT AND DISCUSSION

3.1. Experimental Results

The lubricant directly affects the friction between the die and the workpiece interface. The ring compression test is the most common and reliable test method for contact friction. According to the geometric variation in the test results, the friction coefficients of different oils can be determined. The inner diameter variation of the rings, according to the simulation and experimental method compressed under a certain pressure is given in Table 4. In both cases, the greatest inner diameter change occurred in compressed rings under dry conditions.

Table 4. Inner diameter change of rings

Test Condition	Change in Height (%)	Inner Diameter Change in Experiment (%)	Inner Diameter Change in Simulation (%)
Dry	34.27	23.92	40.74
Vegetable Oil	33.80	18.59	32.26
Motor Oil	26.02	-3.27	-21.30
%1 Nano Oil	26.03	-3.27	-18.96
%3 Nano Oil	23.43	-4.21	-22.63
%5 Nano Oil	26.98	-6.87	-26.68

The friction coefficient values obtained according to the experiment are shown in Figure 5. The friction coefficients of the dry (0.35) and vegetable oiled (0.25) rings are close. However, the friction coefficients of the motor oil (0.03), 1% nano oil (0.035), 3% nano oil (0.028), and 5% nano oil (0.022) are lower than the others. This depends on the way the aluminum rings are lubricated. If the oil fills the inside of the ring, the inner diameter expands with the compression of the ring. The coefficient of friction decreases with the enlargement of the inner diameter of the rings. In dry and vegetable oily rings, the inner diameter is narrowed. Therefore, the coefficients of friction were calculated higher than the other conditions. However, the inner diameter of the motor oil, 1%, 3%, and 5% nano oil rings was enlarged. For this reason, the coefficients of friction were low. These results indicate that the friction between the die and the workpiece can be reduced with proper lubrication.

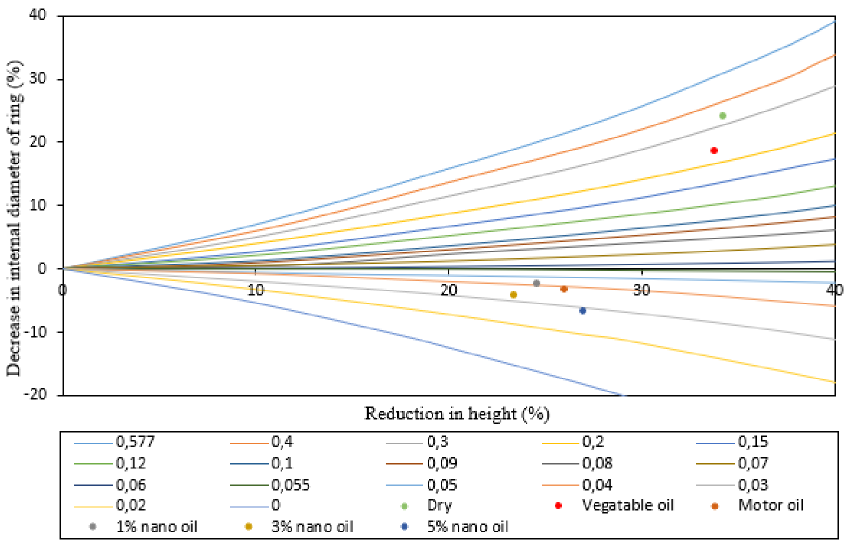

Figure 5. Coefficients of friction under different conditions

3.2. Simulation Results With The FEM

The geometrical variations of the experimental and simulation compressed rings are compared in Figure 6. The figure shows the simulation results as curves, and the experimental results as points. Although there are six experimental results, there are five points in the figure. Because as seen in Table 3, the geometrical changes of the motor oil and 1% nano oil rings are very close to each other. For this reason, the points of motor oil and 1% nano oil overlapped.

According to the figure, there are differences between the experiment and simulation results. In the experiment, the rings were compressed with a hydraulic press machine. Continuous loading of the force applied in the hydraulic press machine is impossible. Therefore, the force on the rings is not continuously loaded but gradually. The sample is stretched as much as the elastic deformation in the loading intervals and then reloaded.

In the simulation with the Abaqus/Standard finite element program, the force is applied continuously during compression. The deformation of the ring starts when the force is applied and continues until the height change (50%) of the ring entered in the program. Thus, a continuous load is made on the ring during compression. In addition, the roughness and friction coefficients on the ring surface are neglected in the simulation. That is, the surface is considered to be smooth.

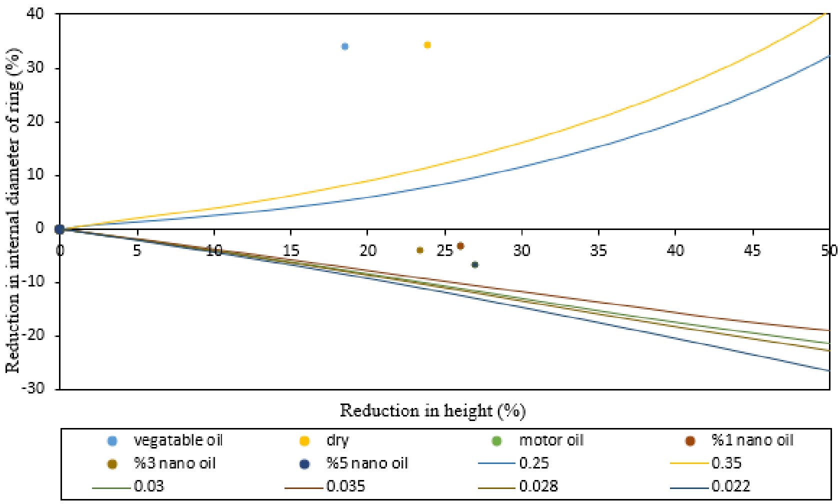

Figure 6. Comparison of experiment and simulation results

3.3. Stress Distribution In Rings

Figure 7 shows the stress values on the rings (dry, vegetable oil, 1% nano oil, motor oil, 3% nano oil, 5% nano oil) compressed by simulation. The highest stress range (difference between maximum and minimum stress values) occurred in the dry ring. Because this ring is compressed in dry conditions without the use of oil to reduce friction. In the experimental and simulation compression test, the highest internal diameter change was obtained in the dry ring (Table 4). This supports the stress results. The lowest strain range was found in the 5% nano oil ring. Since the lowest coefficient of friction is obtained in 5% nano oil, friction is low. Thus, the stress range is less than the other rings. In general, it was determined that the stress range of the rings increased with the increase in the friction coefficient.

According to the figure, more plastic deformation is seen in the middle region of the ring compared to the upper region. When looking at the figure in general, it is seen that the non-uniform stresses and plastic deformation increase with the increase of the friction coefficient. Stresses have occurred in the middle part of the ring, causing the barreling (mushrooming) effect. The barreling in the outer diameter of the ring increases with the increase of the friction coefficient. [16, 30]. When the friction coefficient between the plate and the ring increases, more friction occurs on the upper surface of the ring than on the middle parts. So less displacement takes place at the top. Therefore, barreling (mushrooming) increases in the middle part of the ring. Rasty and Sofuoğlu explained that the moving contact area and the expansion increase with the friction coefficient, and the inner diameter is deformed to become convex [6]. Tatematsu et al. on the other hand, the increase in the friction coefficient causes the material flow to change direction by affecting the resistance on the surface [31]. Therefore, the internal stress is increased, which causes the barrel-shaped narrowing of the inner diameter.

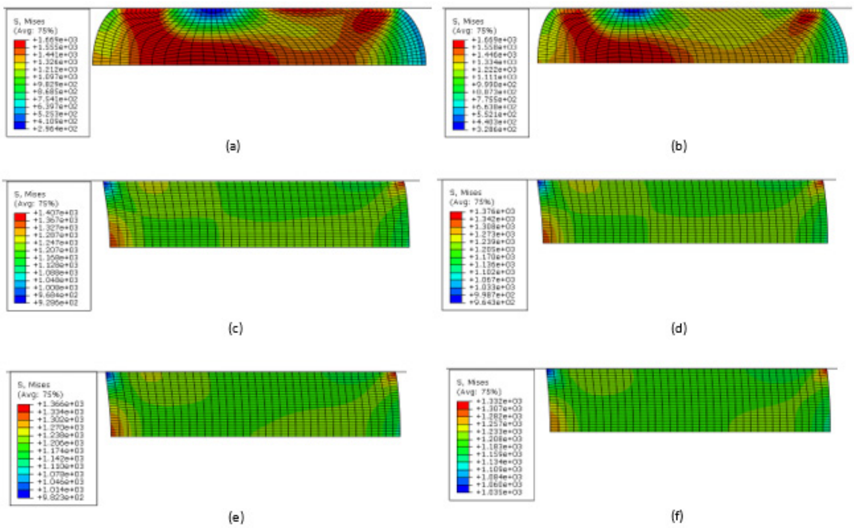

Figure 7. Stresses on rings compressed in simulation; (a) dry, (b) vegetable oil, (c) 1% nano oil, (d) motor oil, (e) 3% nano oil, (f) 5% nano oil

Figure 8 shows the dry ring's stress distribution and plastic deformation regions. As in the work of Zhang et al. the ring is divided into three regions: the hard deformation zone, the easy deformation zone, and the small deformation zone [12]. Since the ring is modeled to be symmetrical, three regions are symmetric about the x-axis. The hard deformation zone is the part of the ring in contact with the plate surfaces. This region is more affected by friction force than other regions. For this reason, shape change is more difficult. The easy deformation zone mostly covers the middle part of the ring. Since there is a distance between the surfaces, it is not affected by the friction force much, and thus deformation is easy. In the small deformation regions, the variation of the inner diameter is observed significantly.

The minimum stress value in the hard deformation region increased with the decrease of the friction coefficient. It has been determined that the maximum stress value in the easy deformation region decreases as the friction coefficient decreases. However, it was determined that the average stress value remained almost constant with the decrease in the friction coefficient.

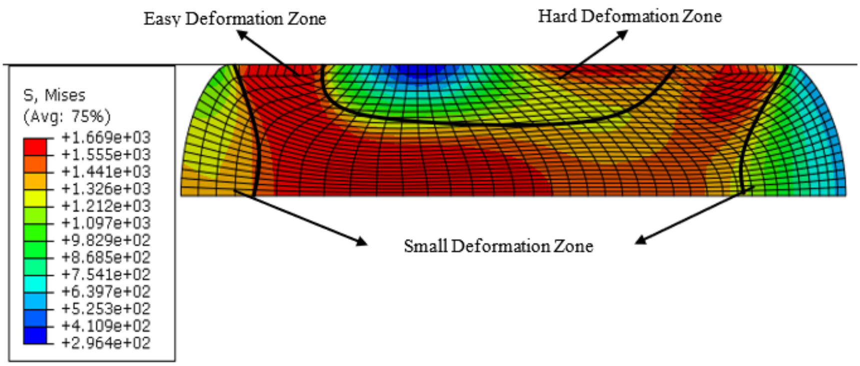

Figure 8. Stress distribution in dry ring

4. CONCLUSION

In this study, the lubricating properties of dry conditions, vegetable oil, motor oil, and nano oil were determined by ring compression test. Al6351 rings were used during the experiment. According to the test results, the ring compression test determined the effect of different oils on the coefficient of friction. Afterward, the ring compression test was simulated with the Abaqus/standard finite element program. Stress distributions in the rings are interpreted by comparing the test and simulation deformation results. The results of the study are presented below:

- The highest (μ=0.35) and lowest (μ=0.022) friction coefficient values were determined in the dry ring and 5% nano oil, respectively.
- The friction coefficient of the rings lubricated with vegetable oil and motor oil is 25.8% and 91.2% lower than the dry ring.
- In addition, the friction coefficient of the rings lubricated with 1%, 3%, and 5% nano oil is 90%, 92%, and 93.7% lower than the dry ring.
- The coefficient of friction values is as dry conditions (0.35), vegetable oil (0.25), 1% nano oil (0.035), motor oil (0.03), 3% nano oil (0.028), and 5% nano oil (0.022), from largest to smallest.

- The best lubricating properties have been obtained in 5% nano oil.
- Differences between the experimental and simulation deformations of the rings were observed. Because the hydraulic press was used in the experiment, the force was applied gradually. In the simulation, the force is applied continuously.
- The stress distribution of the rings is non-uniform with the increase of the friction coefficient.
- In addition, the stress range increased with the increase in the friction coefficient.
- It was determined that the barreling of the rings increased with the increase of the friction coefficient.

Author Contribution Rates :

Design of Study: CGD (%50), FŞ (%50)

Data Acquisition: AT (%60), TCD (%40)

Data Analysis: AT (%25), FŞ (%25), CGD (%25), TCD (%25)

Writing Up: AT (%70), TCD (%30)

Submission and Revision: FŞ (%50), CGD (%50)

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