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Effect of Nanoparticle Percentage in Nano-Lubricants on Friction Behavior in Hot Forging of 17-7PH Steel

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ABSTRACT

The material forming through the forging process is one of the manufacturing methods in which the metal is compressed or subjected to high forces to create high-strength parts. Before the process, a lubricant is added to the mold to increase the metal flow, reduce friction and wear, and help separate the final part from the mold. The importance of lubrication in a hot forging process, and lubrication is the key to quality and productivity. One of the best ways to study the effect of lubricants in this process is ring compression testing (RCT). In this study, the effect of nanoparticles (Aluminum oxide (AL2O3) and Nano-glass) with two different nanoparticles concentrations (0.5wt% and 1wt%) as an additive to base oil (SAE10) at 1050 °C on the friction behavior of 17-7 PH stainless steel using RCT and finite element analysis (FEA) has been studied. Finally, the importance of using Nano lubricants with different nanoparticles concentrations (0.5wt% and 1wt%) in the hot forging process has been investigated. The results showed that nanoparticles as lubricant additives performed better than conventional lubricants (such as graphite) for the frictional behavior of 7-17 PH stainless steel in the hot forging process So that at 1050 ° C the Friction factor by the addition of AL2O3 nanoparticles was reduced about 36% and by the addition of glass nanoparticles about 40% . It was also observed that by adding 0.5wt% Nano-glass and AL2O3 nanoparticles to SAE10 base oil, the coefficient of friction (m) was significantly reduced, but with increasing nanoparticles concentrations to 1wt%, the coefficient of friction (m) was somewhat raised.

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Introduction

Friction at the interface of die/work piece is an important variable and has significant effects on both the work piece and process variables such as deformation load, metal flow and surface quality, and internal structure of the product in metal forming processes [1]. The ring-compression test is a widely accepted way to measure the interface friction between the work pieces and dies. Originally, it was conceived as the qualitative method for comparing the lubrication conditions to the influence of various lubricants onto the contact friction. Nanotechnology is regarded as the most revolutionary technology of the recent century. It can be used in many fields and ushers material science into a new era [2]. Y. Moghani and Y. Dadgar Asl et al. (2022) investigated the friction behavior of 7-7PH stainless steel using RCT and FEA. They showed that in hot forging of 17-7PH stainless steel, graphite lubricant behaves better than aluminum oxide [3]. Y. Moghani and Y. Dadgar Asl et al. (2022) studied the friction behavior of 17-7 PH stainless steel using nano-lubricants in hot forging process. They concluded that nanoparticles as lubricant additives performed better than conventional lubricants. They showed that adding nano-glass presented better results compared to Al_2O_3 nanoparticles [4]. Recently, different researchers reported that nanoparticles can be added as additives to basic lubricants and improve the friction behavior noticeably. Wu, et al.(2007) examined the tribological properties of two lubricating oils, an API-SF engine oil and a Base oil, with CuO, TiO2, and Nano-Diamond nanoparticles used as additives[2]. Choi et al. (2009) showed by using CuO nanoparticles as additives in oil, the average friction coefficient decreased noticeably [5]. Rylski, et al.(2020) studied the effect of nanoparticles, especially ZrO2-based on the friction behavior of lubricants. The result shows that by adding 1wt% ZrO2 nanoparticles to pure lithium grease can decrease the friction coefficient to 50% [6]. Also, using of Cu nanoparticles provided the most effective reduction of friction in comparison to Co and Fe nanoparticles in SAE 10 oil by using tribological test [7]. Ghalmea, et al. (2020) found that the coefficient of friction can be reduced by 22.67 % with the addition of 0.5wt% of AL2O3 nanoparticles in base lubricant oil [8]. In other research, the obtained results from experimental tests revealed that adding 0.5 wt. % AL2O3 nanoparticles to the conventional lubricant improves lubrication property significantly and reduces forming load by 16.39% compared to the conventional lubricant. Frictional behavior of different materials by using different Nano lubricants has been studied by researchers [9]. Ehsan Ghassemali (2022) examined Different categories of forging process such as open-die, closed-die or cold, warm and hot forging, and described the advantages and disadvantages of each [10]. Hot rolling tests of micro alloyed steel were studied under different lubrication conditions, by Hui Wu, et al. (2017). They showed that TiO2 Nano-additive water-based lubricants not only produces the best surface finish, but also results in the thinnest oxide scale of the rolled steels [11]. In other study (2019), the brass alloy CW724R is used. Different lubrication agents are used, including mineral oil and vegetable oil with and without addition of Nano-sized graphite platelets, GnP, in the production of green compacts. The results of the statistical analysis indicate the best mechanical properties when using 0.2 – 0.25 vol. % GnP suspension in oil and 0.15 – 0.2 wt. % oil mixed with the chips before compaction [12]. Shiyuan Luo et al. (2020) check out effect of friction conditions on phase transformation characteristics in hot forging process of Ti-6Al-4 V turbine blade. The results reveal that compared with a less influence on lamellar α + β phase, a good lubricated condition obviously increases the average volume fraction of α phase, while decreases the average values of temperature and β phase volume fraction as well as the distribution uniformities of α and β phases [13]. Seong Won Lee et al. (2020) presented a new concept of critical surface strain to evaluate the lubrication-effective limit for process design in metal forming. They established that the effect of surface strain dominated the metal-forming process, and that the optimized Coulomb friction coefficient changed abruptly at the critical surface strain at which the solid lubricating film used in the process is suddenly disrupted [14]. Alimirzaloo et al. (2017) investigate the effect of Nano lubricants on the surface roughness in the forging process of aluminum alloy. Results show that the Nano lubricants cause a significant improvement on the surface roughness compared to conventional lubricants [15]. Hao Pang et al. (2020) studied formulation of SiO2/oil Nano lubricant for metal forming process. In this study, a nanolubricant with particle size of 3.6 mm exhibited better lubrication on ring samples with dent depth of 4.7 mm, implying that most nanoparticles were encapsulated in the dents facilitating hydrostatic lubrication [16].

In the current study, for the first time, the effect of varying the percentage of nano-lubricant on Friction Behavior of 17-7 PH stainless steel has been investigated. In this research, AL2O3 and glass nanoparticles (in two different Nano particles concentrations 0.5wt% and 1wt%) have been added to oil10 as an additive to investigate the tribological behavior of 17-7PH stainless steel in hot forging by RCT and FEA. Using nanoparticles to study friction behavior of 17-7 PH stainless steel is new and has not been investigated before. Also, this material is widely used in different areas of industry and its friction behavior is noticeable to researchers. Finally, the importance of adding nanoparticles to base oil in reducing friction for hot forging of 17-7PH stainless steel has been presented.

Experimental Procedure and Finite Element Simulation

RCT is used to understand the friction behavior of 17-7PH stainless steel in hot forging with Nano lubricants at two different nanoparticles concentrations (0.5wt% and 1wt%) under different conditions (in 1050°C temperature, 30% and 50% thickness reduction). The stress-strain curve of 17-7PH stainless steel has been illustrated in Fig.1. The experimental data for verifying material in different temperatures have been shown in Fig.1, too. Cylindrical specimens of 17-7PH stainless steel have been tested for verifying material combination and stress-strain curve. The used 17-7 PH stainless steel combination has been listed in Table 1. The nanoparticles (Al_2O_3 and nano-glass) were dispersed in the SAE10 base oil using ultrasonic agitation for 30 minutes to ensure uniform distribution. No surfactants were used, as preliminary tests showed that the nanoparticles remained stable in the oil for the duration of the experiments. The stability of the nanoparticle dispersion was confirmed by visual inspection and by measuring the viscosity of the lubricant before and after dispersion.

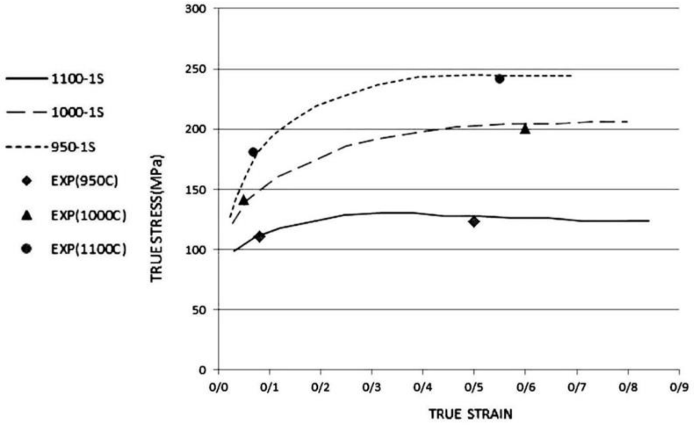


Figure 1. Stress-strain curves from compression tests

Table 1. Material combination

	Cr	Mn	Si	Ni	P	S	C	Al
MIN	16.00	-	-	6.50	-	-	-	0.75
MAX	18.00	1.00	1.00	7.75	0.04	0.03	0.09	1.50

Graphite, Nano-glass (0.5wt%), Nano-glass (1wt%), Nano AL_2O_3 (0.5wt%), Nano AL_2O_3 (1wt%) and SAE 10 (base oil) are used lubricants in this research, as illustrated in Fig.2.

Figure 2. Used lubricants in the experimental procedure

The specifications of SAE 10 oil as oil base and nanoparticles (AL2O3, Nano-glass) have been shown in Table 2 and Table 3, respectively.

Table 2. Physical and chemical properties of SAE 10 oil

Name	Unit	Value
Density	Kgm^{-3}	945
Viscosity kinematic(40°C)	mm^2/s	60
Viscosity Index		85
Pour Point	°C	-21
Flash Point	°C	190

Table 3. Used Nano particles specification

Name	Unit	Value
Density	Kgm^{-3}	945
Viscosity kinematic(40°C)	mm^2/s	60
Viscosity Index		85
Pour Point	°C	-21
Flash Point	°C	190

Experimental procedure has been done by RCT. Different conditions such as lubrication condition (Nano AL AL2O3 2O3 and Nano-glass with two different nanoparticles concentrations (0.5wt% and 1wt%)), temperature (1050°c) and two different thickness reductions (30% and 50%) have been employed in RCT. In the ring compression test, a flat ring-shaped specimen is compressed to a known height reduction. The change in internal and external diameters of the compressed ring is significantly sensitive to friction condition at the die-ring interface, as shown in Fig.3. With increasing deformation, if friction is high, the internal diameter is reduced, while if friction is low, the internal diameter increases. Thus, the change in the internal diameter is used as a friction indicator. The friction condition is expressed as the shear friction factor (m), which can be quantified by comparing the internal diameter of the compressed ring to the values predicted by using various constant shear friction factors in a theoretical analysis [17].

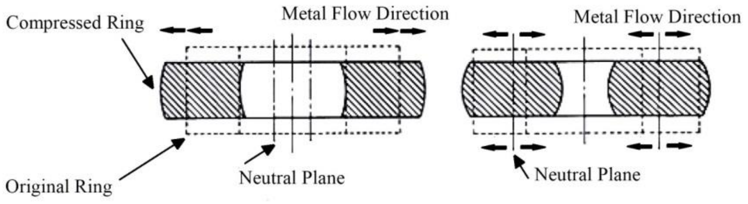


Figure 3. Different friction conditions of ring in RCT, A. after compression by Low friction, B. after compression by high friction [17].

To carry out the ring compression test, the standard ring specimen ratio of 6:3:2 was used. The outer and inner diameters of the ring are D0 = 18 mm and d0 = 9 mm, respectively, and the height is H = 6 mm. The experimental specimens and used screw press have been shown in Fig.4. Different conditions for performing RCT have been shown in Table.4. To achieve more accurate results, experiments have been performed many times.

Table 4. Different RCTs conditions

Test No.	1	2	3	4	5	6
Lubricants type	Graphite	Graphite	Nano-AL_2O_3 0.5wt%	Nano-AL_2O_3 0.5wt%	Nano-glass 0.5wt%	Nano-glass 0.5wt%
Temperature	1050°C	1050°C	1050°C	1050°C	1050°C	1050°C
Thickness percentage	30%	50%	30%	50%	30%	50%
Test No.	7	8	9	10	11	12
Lubricants type	Nano-AL_2O_3 1wt%	Nano-AL_2O_3 1wt%	Nano-glass 1wt%	Nano-glass 1wt%	SAE10 oil (Without Nanoparticles)	SAE10 oil (Without Nanoparticles)
Temperature	1050°C	1050°C	1050°C	1050°C	1050°C	1050°C
Thickness percentage	30%	50%	30%	50%	30%	50%

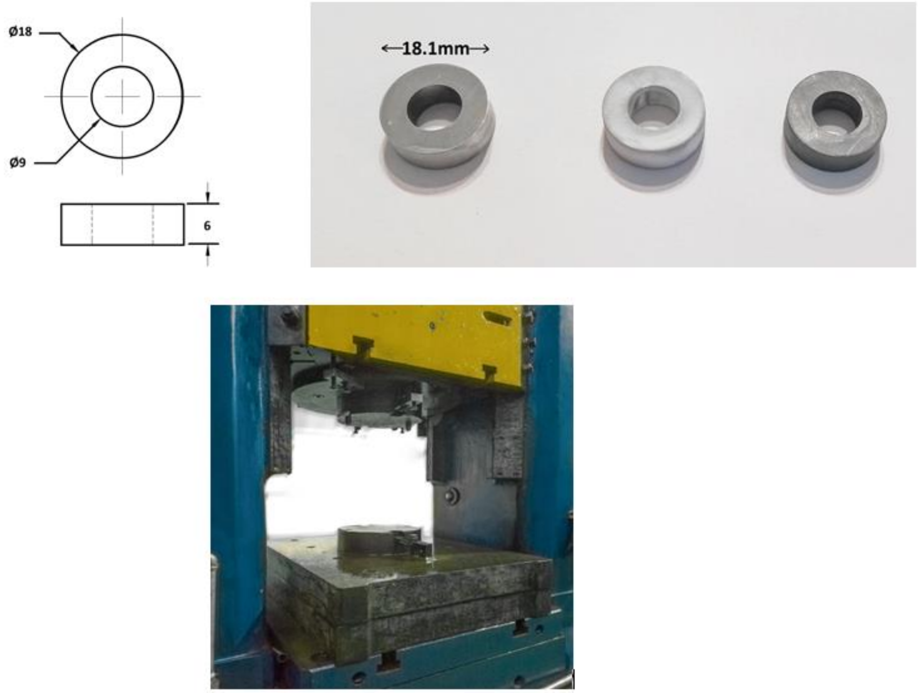


Figure 4. Experimental samples and used screw press

The hot forged samples for both thickness reductions (30% and 50%) have been depicted in Fig.5. As shown, using glass nanoparticle in both different concentrations of nanoparticle (0.5wt% and 1wt%) has the less inner diameter reduction than AL2O3 nanoparticles. Also, using AL2O3 nanoparticle (0.5wt% and 1wt%) has the less inner diameter reduction than graphite lubricant.

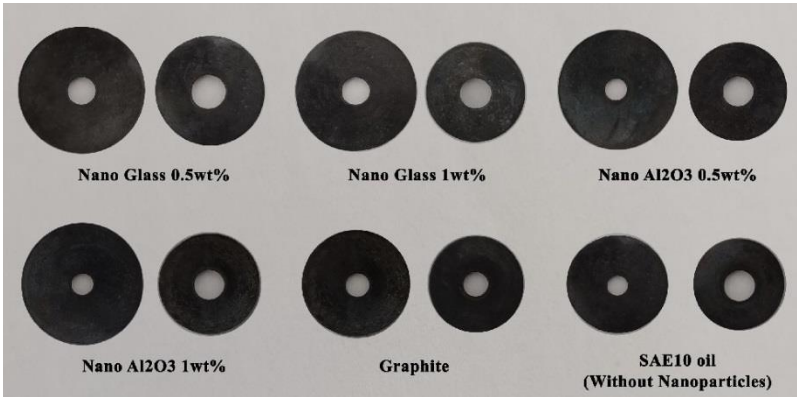
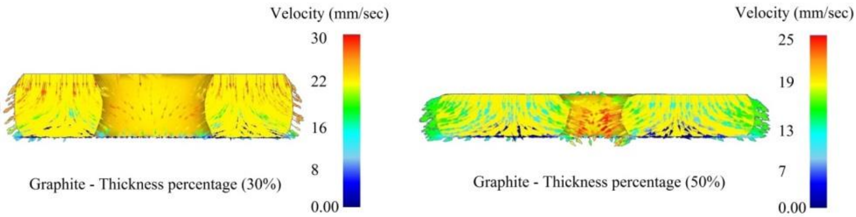
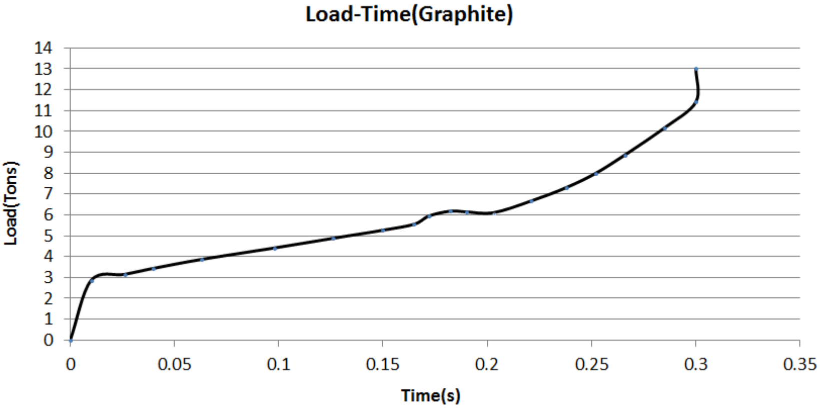


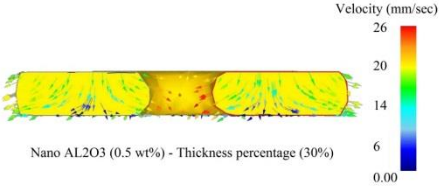
Figure 5. Hot forged samples

For further investigation, a 3D model is developed to simulate the compression process of ring at room temperature. The FEA was performed with the DEFORM-3D Engineering Software.

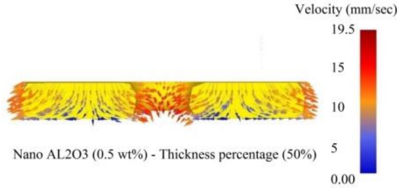
In the FE model, the elastic effect was calculated by using an elastic-plastic material model. The shear friction law is used to define the friction conditions and triangular elements with an edge size of 0.3 mm have meshed for the initial specimen. The meshed model of the sample has been depicted in Fig.6. The dies have been modeled as rigid bodies, while the specimen is a deformable body using 10721 mesh elements and 1754 nodes. The specimen temperature for testing is 1050°C. Also, metal flow by using different lubricants (Nano lubricants and graphite) under different thickness reductions (30% and 50%) at 1050°C has been shown in Fig.6. Load-Time diagram for different simulation conditions has been presented, too.



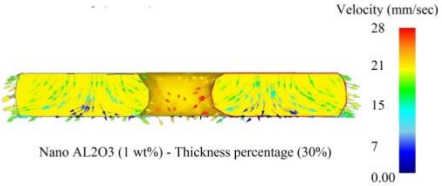




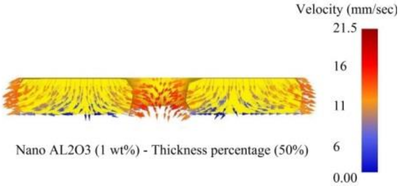
Nano AL2O3 (0.5 wt%) - Thickness percentage (30%)



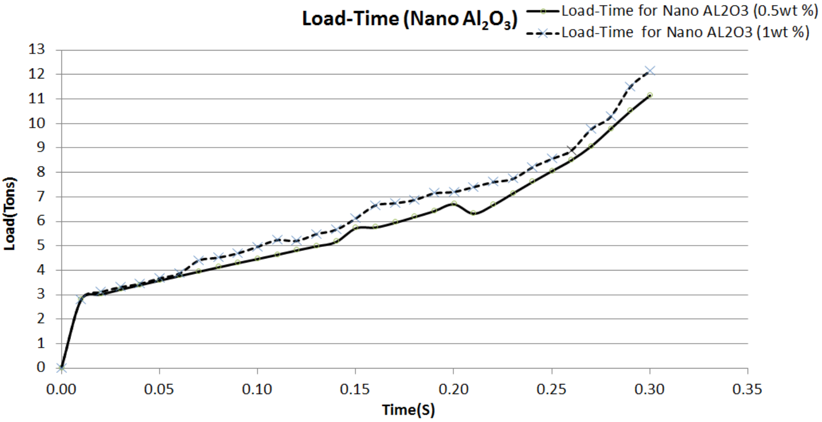
Nano AL2O3 (0.5 wt%) - Thickness percentage (50%)

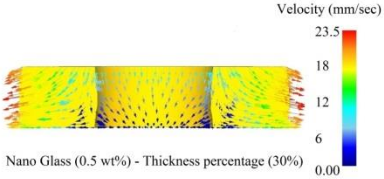


Nano AL2O3 (1 wt%) - Thickness percentage (30%)

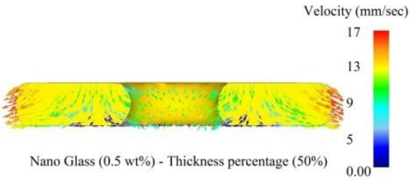


Nano AL2O3 (1 wt%) - Thickness percentage (50%)

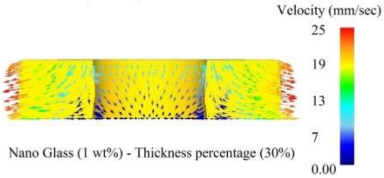




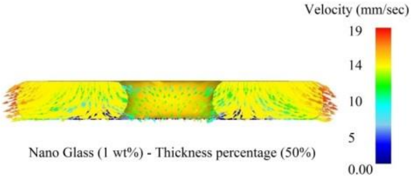
Nano Glass (0.5 wt%) - Thickness percentage (30%)



Nano Glass (0.5 wt%) - Thickness percentage (50%)



Nano Glass (1 wt%) - Thickness percentage (30%)



Nano Glass (1 wt%) - Thickness percentage (50%)

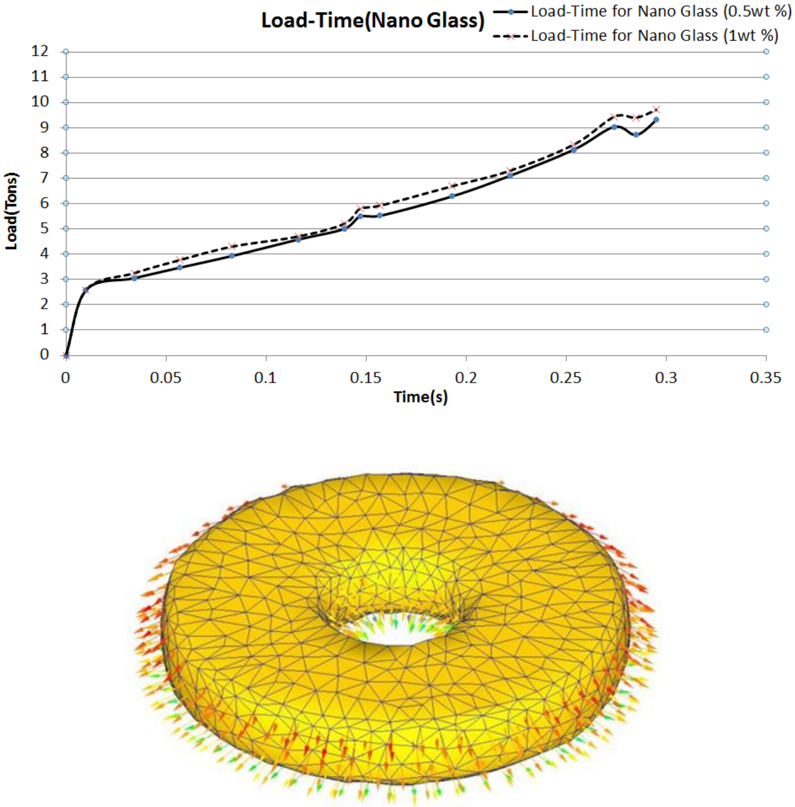


Figure 6. Comparison of metal flow and Load-Time diagram by using different lubricants (Nano lubricants and graphite) under different thickness reductions (30% and 50%) in 1050°C, And .meshed model of the sample in FEA

Result and discussion

Comparisons between FE and experimental results have been made by considering inner and outer diameter change. Table5 Shows the comparison of diameter change between calculated values by FE simulations and experimental values by hot ring-compression tests. As shown, the error between FE simulation and experimental results are in fluctuates between 0.4% and 1.54%.

Table 5. Simulated and experimental results (dimensions of ring) by using different lubrication conditions in 1050 °C temperature

					No. of experiments				
Lubricant type	T (˚C)	Height Reduction (%)	Ring Dimensions	Simulation	1	2	3	4	Ave. Dim
Nano- AL$_2$O$_3$ 0.5wt%	1050	50%	Inner Dim.	5.90	6.11	5.67	5.82	6.22	5.95
			Outer Dim.	25.8	25.7	25.45	25.2	25.65	25.5
		30%	Inner Dim.	7.81	7.73	7.71	7.95	7.86	7.81
			Outer Dim.	22.38	23.1	22.32	22.2	22.4	22.50
Nano-glass 0.5wt%	1050	50%	Inner Dim.	6.20	6.41	6.09	6.17	5.75	6.12
			Outer Dim.	27.1	26.91	26.68	27.83	26.61	27.03
		30%	Inner Dim.	7.95	7.82	7.76	8.2	8.3	8.02
			Outer Dim.	23.72	23.24	22.98	23.72	23.31	23.32
Graphite	1050	50%	Inner Dim.	5.23	5.45	4.95	5.74	5.2	5.33
			Outer Dim.	22.77	22.7	22.45	22.8	21.95	22.47
		30%	Inner Dim.	7.61	7.55	7.2	7.38	7.75	7.47
			Outer Dim.	19.98	19.85	20.15	19.65	19.45	19.77
Nano- AL$_2$O$_3$ 1wt%	1050	50%	Inner Dim.	5.75	5.9	5.95	5.45	6.05	5.83
			Outer Dim.	25.31	24.85	25.15	26.5	25.5	25.51
		30%	Inner Dim.	7.71	7.44	7.45	7.52	7.95	7.59
			Outer Dim.	22.25	22.4	22.95	22.45	21.55	22.33
Nano-glass 1wt%	1050	50%	Inner Dim.	6.10	6.35	6.15	5.8	5.95	6.06
			Outer Dim.	26.2	26.85	25.95	25.85	26.6	26.31
		30%	Inner Dim.	7.85	7.72	7.91	7.82	7.55	7.75
			Outer Dim.	22.48	22.5	22.5	23.15	23.05	22.82
SAE10 oil (Without Nanoparticles)	1050	50%	Inner Dim.	4.65	4.45	4.5	4.95	4.4	4.575
			Outer Dim.	20.85	21.15	21.8	20.95	20.55	21.11
		30%	Inner Dim.	7.46	7.4	7.2	6.9	7.9	7.35
			Outer Dim.	18.65	18.85	18.65	19.15	19.1	18.93

The impact of Nano particle concentrations (without Nano particles, 0.5wt% and 1wt%) on friction factor (m) has been investigated. As illustrated in Fig.7 by adding 0.5wt% of Nano-glass and AL2O3 nanoparticles to oil base SAE10, Friction Factor (m) has been reduced noticeably. By increasing nanoparticles concentration to 1%wt, Friction Factor (m) has been raised. But still, using nanoparticles with the concentration of 1wt% has better lubrication performance than not using nanoparticles.

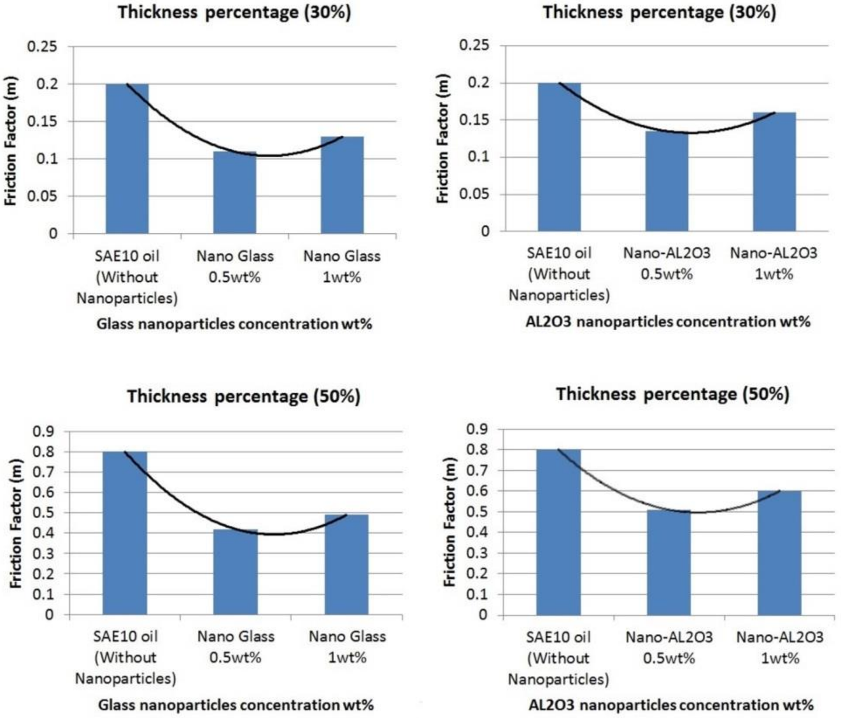


Figure 7. Relationship between friction factor (m) and nanoparticle concentration, using different lubricants (Nano-glass and Nano AL2O3) with different thickness reductions (30% and 50%) at 1050 ° C

Maximum deformation force to rich 50% thickness reduction has been considered as another parameter that has been obtained by Load-Time diagram. Fig.8 shows the maximum required force to reduce 50% thickness for base oil SAE10, Nano-glass 0.5wt% and 1wt%, graphite, AL2O3 nanoparticle 0.5wt% and 1wt%. The minimum required force is related to Nano-glass 0.5wt% which is 2% less than using AL2O3 nanoparticles 0.5wt%. Also, by increasing the nanoparticles percentage from 0.5wt% to 1wt%, the deformation force has been reduced about 0.5-1 %.

In addition, this study shows required deformation force in hot forging by using Nano lubricants is lower than using graphite lubricant and base SAE10 oil. Consideration of Load-Time diagram shows the initial step of the Load-Time diagram is somewhat similar, because contact has been started and lubricant has less effect. But, after making pressure by top die on the part, lubricants are more effective.

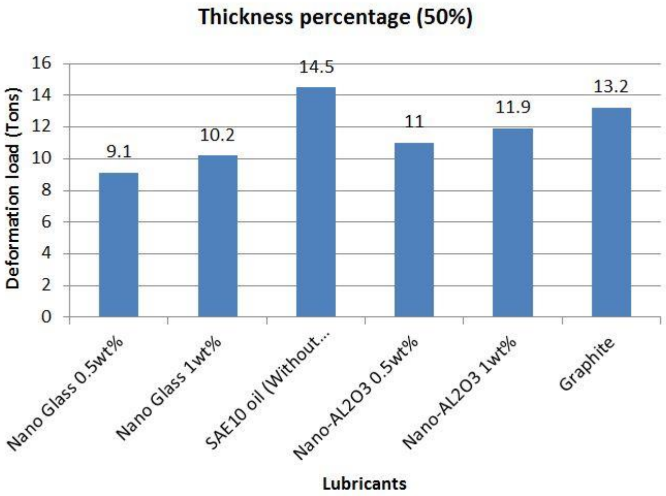
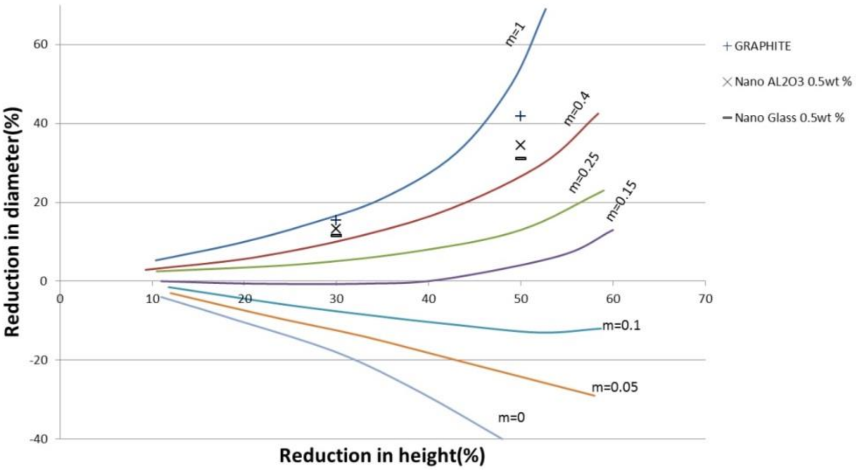


Figure 8. Deformation loads of different lubricants in thickness reduction 50%

Finally, using the simulation results, the 17-7PH stainless steel calibration curve at 1050 ° C was obtained as shown in Fig.9. As shown adding nanoparticles (Nano AL2O3 and Nano-glass) with different concentrations (0.5wt%, 1wt%) in SAE 10 oil has better friction behavior (lower friction factor) than general lubricant (graphite). Also, Nano-glass lubricant with 0.5wt% and 1wt% has better friction behavior than Nano AL2O3 lubricant with 0.5wt% and 1wt%.



		Reduction in Height (%)	
		30 %	50 %
Reduction in Diameter (%)	SAE10 oil (Without Nanoparticles)	17.1	48.3
	Graphite	15.4	41.8
	Nano AL_2O_3 1wt %	14.3	36.1
	Nano AL_2O_3 0.5wt %	13.2	34.4
	Nano Glass 1wt %	12.8	32.2
	Nano Glass 0.5wt %	11.6	31.1

Figure 9. Calibration curve of 17-7PH stainless steel in 1050°C by FE simulation

Given that the plastic deformation and temperature history in the SZ have a significant impact on the microstructure of welds, understanding the strain distribution during friction stir welding is crucial for effective design and process management. Figure 4 illustrates the strain distribution across the cross-section of welds manufactured using various probe types. It is evident that the strain generated by the cylindrical pin is the lowest compared to other probe designs, indicating insufficient material flow during the welding process. Conversely, samples produced with edged probe tools exhibit significantly higher strain levels. Furthermore, the area affected by the strain from tool rotation is larger in tools with edged probes than in those with circular designs. Tool probe profiles that feature flat sides, like triangular and square shapes, have an associated measure of eccentricity, which is the ratio between the tool's dynamic volume swept and its static volume. The triangular tool endures the highest level of strain because it has the largest revolving arm in comparison to other pins. Nevertheless, it generates a minimal pulsation effect, resulting in the strain affecting the smallest area.

Conclusion

- The RCT is a reference method for studying friction behavior in cold forging process. But, this method is not applicable in hot forging for special materials. Thus, the comparison of obtained results by RCT and FEA is important for investigating the friction behavior of any material. AL2O3 Nanoparticles and Nano-glass particles in comparison with general lubricant (graphite) have a noticeable effect on the friction behavior of 17-7 PH stainless steel in the hot forging process. Analysis of acquired results can be expressed as follows:
- The experimental and simulated results show that the average difference in the inner and outer diameter of the ring between RCT and FEA data is about 5%, approximately. But, the FEA results would be more reliable than RCT.
- For 17-7PH stainless steel at 1050°C, the friction factor by adding AL2O3 nanoparticles has been reduced by about 36% and by Nano-glass particles by about 40%, respectively. Thus, adding Nano-glass particles has a better result than AL2O3.
- Friction calibration curve of 17-7 PH stainless steel for different friction conditions at 1050°C has been diagramed.
- It should be noted that a certain amount was acquired for nanoparticles concentration which can lead to minimum friction factor. According to obtained results, for an optimum amount of nanoparticles concentration, using Nano-glass particles 0.5wt% are able to realize a lubrication performance in the range of used lubricants.
- Following the improvements in frictional conditions, the deformation loads are reduced due to the utilization of Nano lubricants which is very effective in reducing the energy consumption.
- Future work could focus on investigating the effect of different nanoparticle sizes on the friction behavior of 17-7PH stainless steel in hot forging. Additionally, other types of nanoparticles, such as TiO2 or SiO2, could be explored to determine their effectiveness as lubricant additives. Further studies could also include microscopic analysis of the worn surfaces to better understand the wear mechanisms involved in the presence of nanoparticles.

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