Dry Friction and Wear Performance of Micro Surface Textures Generated by Ultrasonic Assisted Face Turning

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Abstract
Nowadays the surface texturing has been widely recognized as a usable capability to improve the tribological systems. In this paper, ultrasonic assisted turning (UAT) isperformed to create the micro textures on the flat faces. Micro surface texturing ismade on the Al7075-T6 by the UAT in the face turning process. Then, the influences of cutting speed feed, vibration direction and vibration amplitudeare studied.The effects of process parameterson the friction and wear behaviors of un-textured and textured patterns areinvestigated by the full factorial method. Microscopic images demonstrate the creation of micro dimples on the surfaces.Experimental results showed that textured surfaces can decrease the average friction coefficient and wear rate. The friction coefficient of surfaces generated by the UAT processwasdecreased about 10% in comparison to surfaces generated by conventional face turning.Moreover, because of existence of micro-dimple arrays in surfaces generated by the UAT process, proportion of contact between the pins and textured surfaces reduces. Cutting speed and feed effect on both of the average friction coefficient and wear rate.By increasingofthe cutting speed, feed, vibration amplitude and vibration direction (angle), the average friction coefficient and wear reduce.

Keywords
Ultrasonic Assisted Face Turning, Sliding Wear, Surface Topography, Wear Testing.

1. Introduction

Nowadays, demands for the advanced instruments and materials with the best surface quality and tribological properties can be observed everywhere. In this regard, surface texture has been widely recognized as viable toolsto reduce the friction coefficient and wear resistance of tribological systems.

Surface texture includes asperity surfaces whichare created by regular micro-dimplearrays compared toideal smooth surfaces.Previous researcheshave confirmed that some non-smooth surfaces which include micro-array features, called textured surfaces, have beenconsidered to present better tribological properties than un-textured surfaces [1-3].

The idea of surface texturing was originated in the 1960. As the first research, Hamilton et al.proposed that the surface textures have a crucial role to produce additional hydrodynamic lubrication.There are various novel machining techniques to produce the surface textures for controlling the tribological properties. These techniques are generally classified into the mechanical, energy beam techniques, etching and ion beam texturing [4].

Patterson and Jacobson (2003) investigated the generated surface textures by lithography and anisotropic etching of silicon wafers. Tribology evaluations were done in the reciprocating sliding under dry and boundary lubricated conditions. Test results showed improvement of the relation between the textured surface and tribology behaviors in bothof the sliding conditions [5]. Etsion produced the micro-dimples by using the laser surface texturing (LST) technique.Also, theoretical models and experiments were performed to study the capabilitiesof LST to influence on tribological properties. Their results confirmedthat the friction was reduced bythe LST technique compared to the non-textured surfaces [6].

Patterson and Jacobson (2004) studied the tribological properties of micro textured diamond-like carbon coated surfaces by usingreciprocating sliding test method under starved lubrication boundary conditions.The ability to feedlubricantinto the interface of a sliding surfacesdepends on several factors such asthe orientation, size and shape of the texture patterns [7]. Karamıs et al. investigated the tribological behaviors of extruded Al–SiC composites by applying the reciprocating extrusion (RE).Test results showed that there areno systematic relationships between the wear loss and hardness.Moreover, there were no systematic relationships between the wear loss and pass numbers of the RE [8].

Sudeep et al. (2013) created dimple-shaped textures on a surface of AISI 52100steel by using the laser process.Also, theystudiedthe friction and wear behaviors by means of reciprocating friction and wear testing machine [9]. Li et al. (2014) created some dimples on the copper surface by the application of laser peen textured. Then, they carried out the experiments of wear and friction in the vertical loads and different sliding speeds. According to their results, wear and friction behaviors wereimproved [10].

Numerous manufacturing processes have been suggested and applied togenerate the micro-structures.However,the efficient and accurate generation of micro-structures hasremained a challenge. The laser ablation, despite of its flexibility in the field of micro-structure generation, is not acceptable for mass productionbecause of high cost and time consuming[11]. Micro-stamping, as a conventional process, is ideal for mass production, but it has limitations on the brittle and high strength materials.Micro-Electro-Mechanical Systemsare basically 2D processing technologies, so they are not proper for the 3D freeform surfaces. As a result, researches have continued to achievea fast, accurate, and flexible fabrication method of micro-texturedsurfaces [12].

The ultrasonic assisted machining (UAM) process is a machining method to create the precision surfaces.This method, by exerting the vibration components to the tool, leads to oscillatory changes during the machining process. Finally, micro texturesare created on the surface of the workpiece. There are various unique reasons that surface textures, generated by UAT, have significant difference related to the other existing processes. These reasons includethe improvement of accuracy, tool life, processing efficiency, surface quality and high removal rate [13].Moreover,the reduction of the cutting forces and creation of regular micro-textures without limitation on the material removal rate are other useful aspects[14].Tool geometry, machining parameters and thecontoursof the vibration trajectoryeffecton the shape and pattern of generated textures [15].

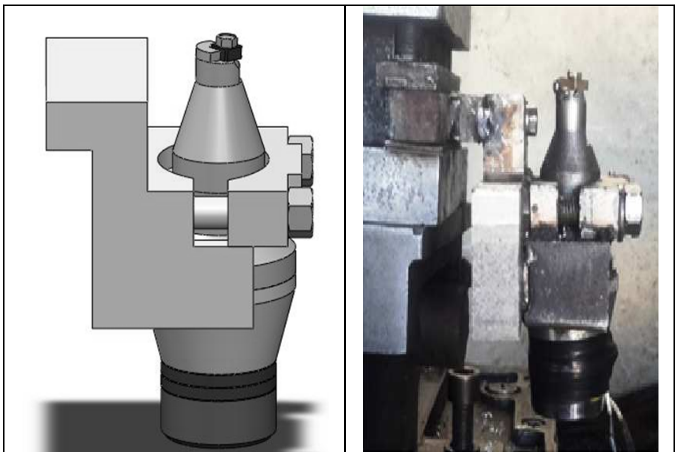
Suzukiet al.utilized 4-axis CNC machine to investigate the groove and dimple pattern sculpturing of the surface textures [16].Xing et al.performed a kinematic analysis on the path of the tool tip in the process of ultrasonic vibration milling. Also, theyexamined the wear and friction properties of machined surfaces. Their results showed that the surface textures, created by UAM,have a vital role in the trapping lubricant.Hence, these surfaces lead to a better friction resistance compared tothe surfaces machined by the traditional milling process [17].Shen and Thaoused the ultrasonic vibration-assisted milling process to prepare two surfaces with complex micro textures.Mentionedsurfaceswerecalled the micro scale textured (MST) and microfurrow textured (MFT). Experimental results showed that the tribological properties can be greatly improved by the micro textures formed by the UAM method.Also, theyrealizedthe MFT surfaceshavea better tribological performance than the MST surfaces [18].

According to the literature, there is no researchto evaluate friction and wear properties of the micro textured surfaceswhich are producedbythe UAT. The goal of this paper is making ofmicro texture surfaces in the ultrasonic assisted face turning. In order to easier application of wear and friction tests, a flat face is produced.Also, some flat faces such as seat and thrust bearing can be produced by the turning process. So,the tribological properties of the textured surfaces are comparedto the un-textured surfaces. A full factorial design of experiments (81 sets of experiments) is employed. Then, the influences of cutting speed feed, vibration amplitude and direction in CT and UAT processesarestudied on micro textures, friction and wear properties of surfaces.

2. Experimental

2.1 Ultrasonic equipment

To generate micro texture, longitudinal vibration tool was used which is made ofa transducer attached to the horn with the power of 400 watts.Horns shouldbe designed in such a way that the vibrations at the tool tip have hadthe highest amplitude.Strengthening of the amplitude is obtained by the reduced cross-sectional area of the horn along the transducer axis. The horn's head, wherethe most movementoccurs, is the bestpositionto connect the insert to the set[19]. The tool's seat on the horn was constructed by the insert's features:the relief angle of 5° and the cutting edge angle of 45°. A high frequency (27 KHz) ultrasonic power supply was used to generate ultrasonic vibrations. Appropriate voltages for generating the vibration amplitudes of 8 and 16 µm (zero to peak amplitude) were recorded and measured.The 3D image of the designed configurationis shown in Figure 1 (a).



(a) (b)

Figure1. a) 3D model of the designed vibro-tool sets, installation modes of the fixture.

2.2 Machine tool, tools and materials

The UATexperimentswere performed on a TN50BR universal lathe.To changethe depth of micro dimples, three ultrasonic fixtureswere consideredin three angles (0°, 15° and 30°). Installationofthe vibro-tool set in three different directions are shown in Figure 1 (b-d).

The cutting tools were Tungsten Carbide inserts (WC) with the technical specification of SNMG 12 04 08. All inserts had the same geometry with the zero obliquity and without chip break.Micro surface textures weres made on Al7075-T6workpiece. Table 1 shows the chemical composition of Al7075-T6.In this study, a disk shape work piece of Al7075-T6 with the outerandinner diametersof 50, 13 mm and the thickness of5mm wasused.

Table1. The chemical compositions of AI7075-T6.

Elements	Al	Zn	Mg	Cu	Fe	Cr	Mn	Ti	Si
Compositions (%)	Bal.	5.6	2.4	1.6	0.5	0.24	0.3	0.2	0.4

2.3 Design of experiments and measurements

In the present research, all experiments were performed in the full factorial design. Feed, cutting speed, vibration amplitude and vibration direction were selected as the researchparameters. These four parameters have the significant effect on the generating micro surface textures. Selected factors and the levels of experiments are listed in the Table 2. The levels of factors were chosen by primary experiments, in a manner that process generates suitable micro textures. Here, the vibrating amplitude of 0μm means that the experiments have been performed without ultrasonic vibration. In other words, samples were machined by conventional faceturning. For all experiments, a constant depth of 0.25mm was applied.

Table2. Factors and chosen levels

Factors	Level 1	Level 2	Level 3
Cutting speed, *Vc* (m/min)	22	35	56
Feed, *f* (mm/rev)	0.128	0.205	0.281
Vibration amplitude, *a* (μm)	CT	UAT_{a1}	UAT_{a2}
	0	8	16
Vibration direction angle, *d* (Degrees)	UAT_{d1}	UAT_{d2}	UAT_{d3}
	0	15	30

2.4 Friction and wear evaluation tests

Pin-on-disk friction and wear tests were executed to investigate the friction and wear behavior of textured and un-textured surfaces. The chrome steel pin was fixed, while the sample rotates against the pin. All tests were performed at a normal (vertical) load of 10 N and a constant distance of 300 m. The dynamic data of friction coefficient was recorded during the tests. The surface topography in the worn areas of Al7075-T6 and the chrome steel pin were studied using anoptical microscope (Dino-Lite- AM4113ZT). The schematic and actual views of pin-on-disk test configuration are shown in Figure 2.

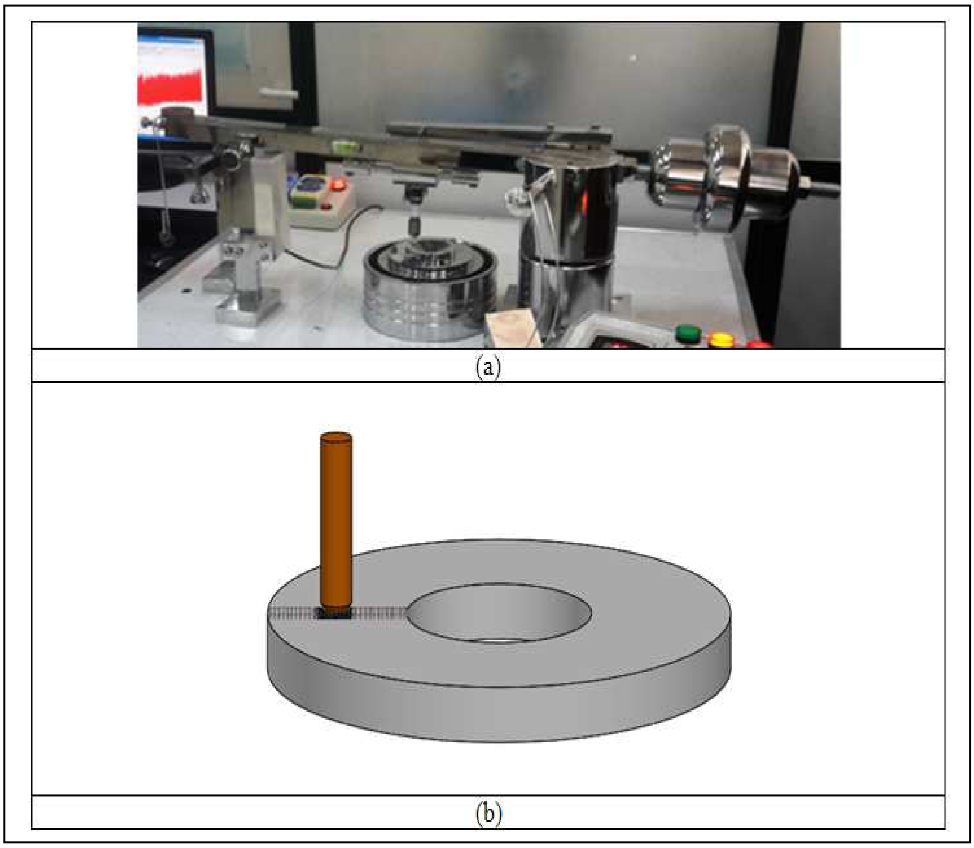


Figure2. Setup for friction and wear evaluation tests; (a) pin on the disk test machine, (b) schematic view of the surface sliding against the chrome steel pin.

3. Results and Discussion

The influence of each parameter used in UATexperimentsare investigated on the surface texture, surface hardening, friction and wearproperties of surfaces. The results are presented in the following sections.

3.1 Surface texture results

Micro-dimple arrays are illustrated according to the feed direction in Figure 3. With the increasing of feed, the distance between the dimples increases in the feed direction. In other words, the increasingof feed results in the expansion of micro-dimples in the feed direction.

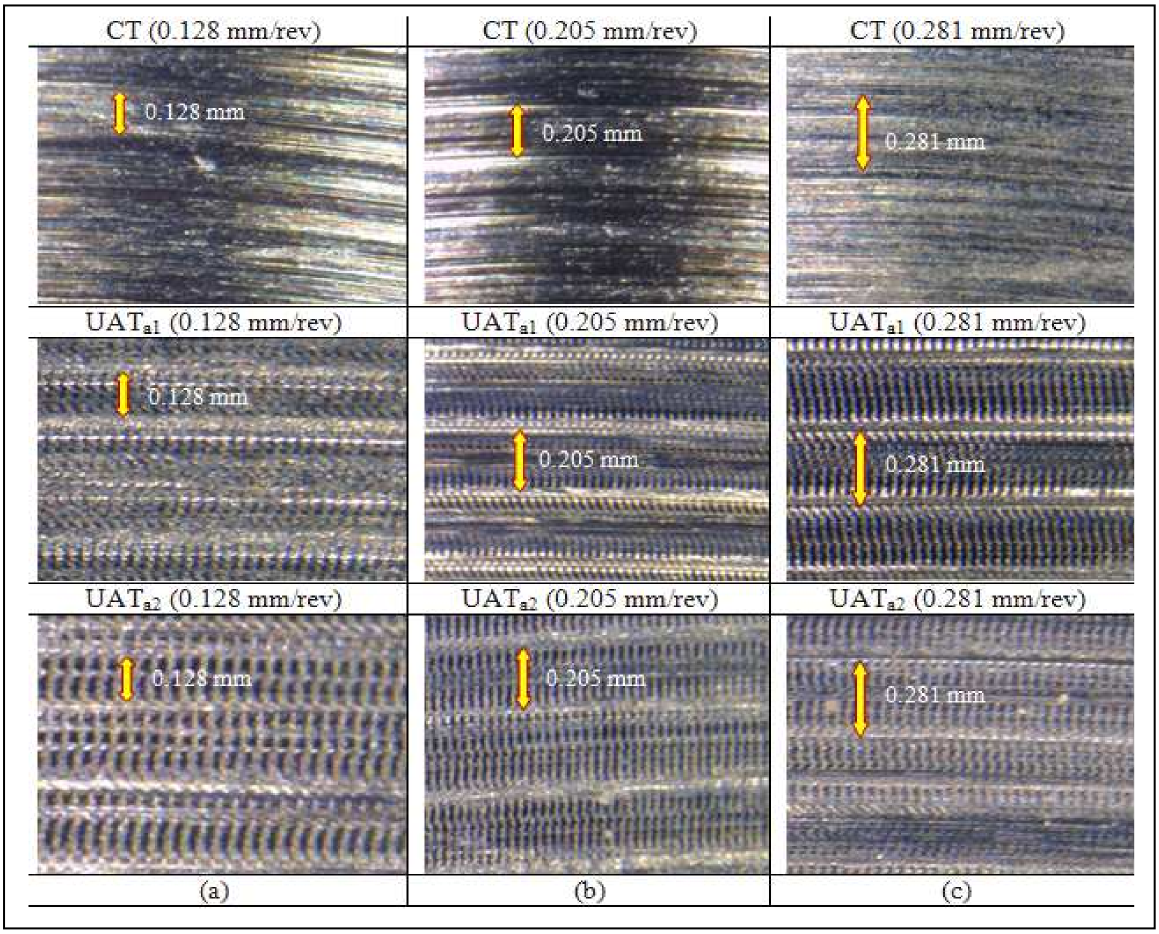


Figure3. Comparison of surface texture for the vibrationangle of 15˚ according to the influence of *Vc* of 56 m/min and different feed levels.

Therefore, as can be observedin Figure4, by increasing of the vibration direction (α) in the experiments, the depth of micro-dimples increases.

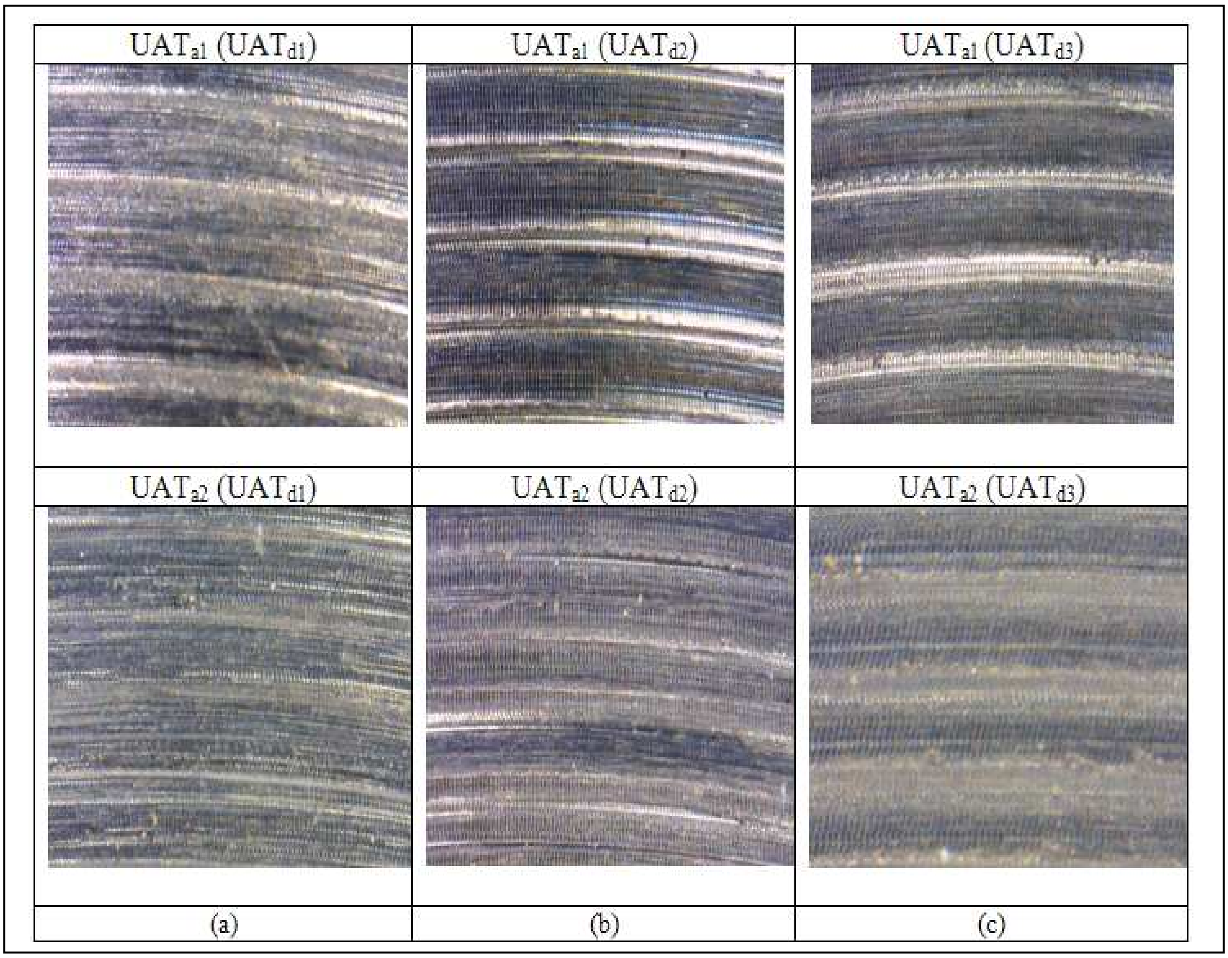


Figure4. Comparison of surface texture for the *Vc* of 56 m/min and feed of 0.281 mm/rev according tothe different vibration directions; (a) 0°, (b) 15°, (c) 30°.

3.2 Friction and wear

3.2.1 ANOVA results of theaverage friction coefficient

Analysis of variance for the average friction coefficient was performed by using the Minitab software with the confidence level of 95%. The results (Table 3) show that the vibration amplitude (56.75%) has the mostinfluenceon the average coefficient of friction. The parameters of cutting speed (30.43%) and vibration direction (6.07%) are other influential factors.

Table3: ANOVA results of theaverage friction coefficient.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Vc (m/min)	2	0.0180618	0.0180618	0.0090309	113.61	0.000	30.43
f (mm/rev)	2	0.0003526	0.0003526	0.0001763	2.22	0.120	0.59
d (deg)	2	0.0036065	0.0036065	0.0018032	22.69	0.000	6.07
a (µm)	2	0.0336865	0.0336865	0.0336865	423.79	0.000	56.75
Error	72	0.0036565	0.0036565	0.0000795			6.16
Total	80	0.0593639					100

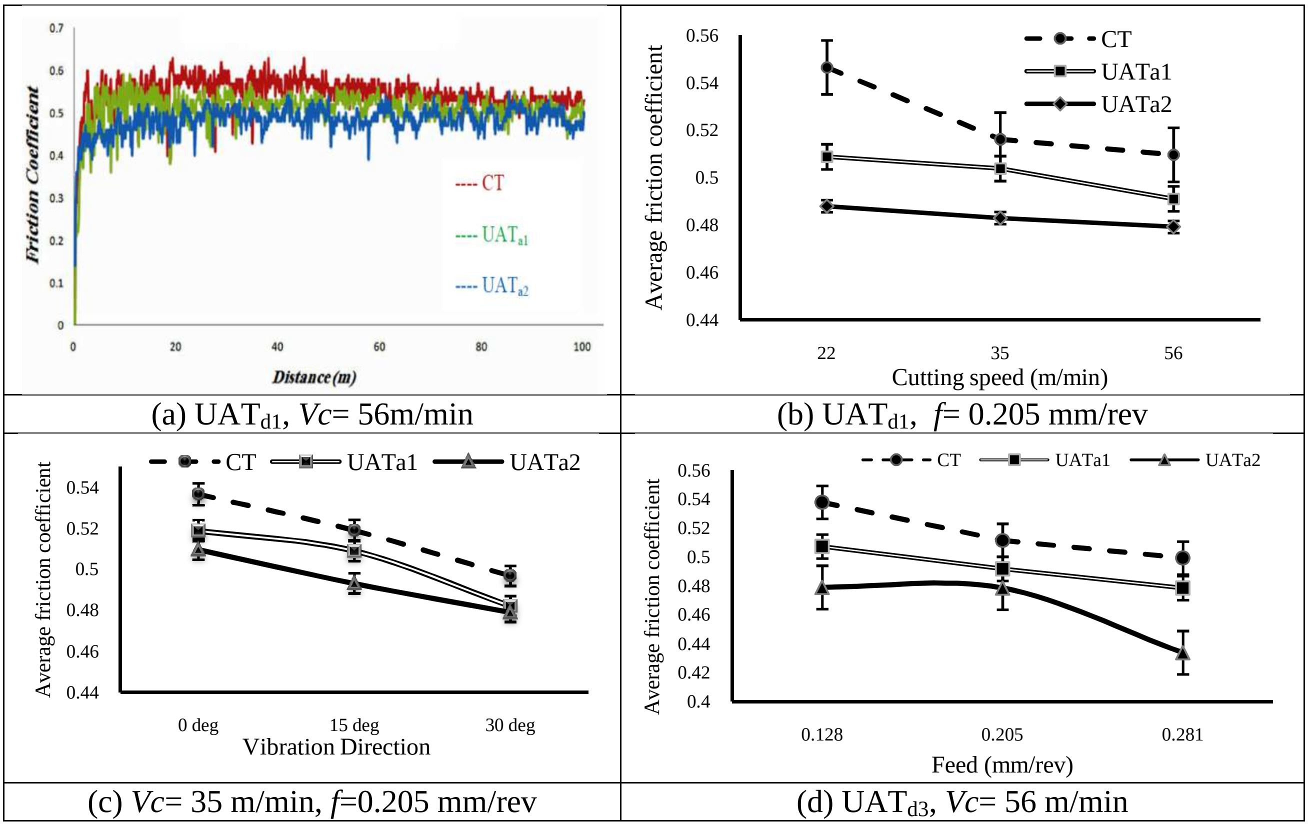
3.2.2 Effectof theprocess parameters on the friction coefficient

Figure 5(a) shows the variations of friction coefficient of three types of un-textured and textured surfaces (CT, UAT_{a1} and UAT_{a2}). Under all experimental conditions for UAT specimens, friction coefficient of textured surfacesis lower than surfaces generated by the CT process.So that, the

UAT_{a2} process reduces friction coefficient in comparison to UAT_{a1} process (Figure. 5(b)). The average friction coefficients of the UAT_{a1} andUAT_{a2} specimens decreaseby 4–10% and 6–15% compared to CT surfaces, respectively.
The average values of the friction coefficients, achieved from textured and un-textured specimens at different cutting speeds, are illustrated in Figure 5(b). According to this figure, by increasing of cutting speed, the average friction coefficients decrease.
Increasing of *Vc* leads to the expansion of micro dimples in the cutting direction. In other words, by increasing of *Vc*, the distance between the dimples gets larger. Hence, the density of dimples (the number of dimples) is decreased in a given area. The number of dimples in the UAT can be calculated as below:

$$DN = t \times fr, t = L / Vc \Rightarrow DN = fr \times L / Vc \quad (1)$$

Where, fr is vibration frequency, L is cutting length, Vc is cutting speed and DN is dimple numbers in a specific cutting length. It is obvious that the number of dimples has an inverse relation to the cutting speed. Also, as can be seen in Figure 4, by changing of the vibration direction along the cutting direction, the depth of dimples increases according to the ratio of sin (α). Therefore, by increasing of the vibration direction angle (α), the depth of micro-dimples increases.
Figure 3 shows micro-dimple arrays in the feed direction. Increasing of feed results in the expansion of micro-dimples in the feed direction. In other words, by increasing of feed, the distance between the dimples gets larger in the feed direction. UAT process lead to increase in summits density. So, the contact of summit points in two frictional components increased that leads to decrease plastic deformation of asperity areas during the sliding.
As discussed in the section 3-1, increasing of the cutting speed leads to the greater length of the micro-dimples. So, in the UAT process, by increasing of the cutting speed, the ratio between the interfacial and projected area, $S_{dr,}$ decreases. Hence, the conflict of two connected surfaces (two frictional components) decreases. On the other hand, it can be concluded that by increasing of the cutting speed, summits density is declined.



(a) UAT$_{d1}$, *Vc*= 56m/min | (b) UAT$_{d1}$, *f*= 0.205 mm/rev

(c) *Vc*= 35 m/min, *f*=0.205 mm/rev | (d) UAT$_{d3}$, *Vc*= 56 m/min

Figure5. a) Measurement of the friction coefficient, comparison of friction coefficientinCT, UATa1 and UATa2withthe different values of (b) cutting speed, (c) vibration direction, (d) feed.

As can be seen from Figure 5(c), by increasing of the fixture angle, the average friction coefficients decrease. The average friction coefficients of CT, UAT$_{a1}$ and UAT$_{a2}$ specimens at different feed levels are illustrated in Figure 5 (d). According to this figure, byincreasingofthe feed, the average friction coefficient decreases.

3.2.3 Investigation of worn sample's surfaces

Figure 6 (a-c) shows the morphology of worn surfaces of the un-textured surface (CT) textured surfaces by UAT$_{a1}$ and UAT$_{a2}$, respectively.

Figure 6(a) shows that the un-textured surface is almost worn. However, the wear scars of un-textured surfaces become much wider. Material loss and scratches indicate that abrasiveand adhesive wear occur during the test.As shown in Figure 6 (b)-(c), the wear scar width of textured surfaces, created by the UAT, is narrower than un-textured surfaces which are generated by CT.

In textured surface generated by the UAT$_{a1}$, fewer scratches and more moderateworn tracks were observed in comparison to the un-textured surface. Also in the textured surfaces by the UAT$_{a2}$, fewest scratches and mildest worn tracks were observed in comparison to the textured surface created by the UAT$_{a1}$.

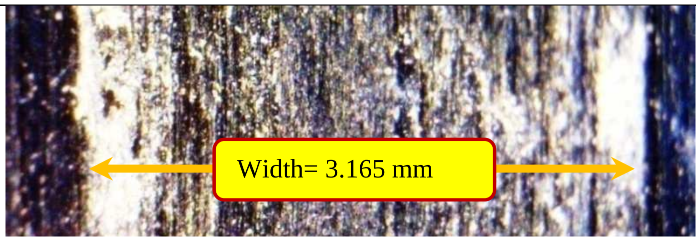
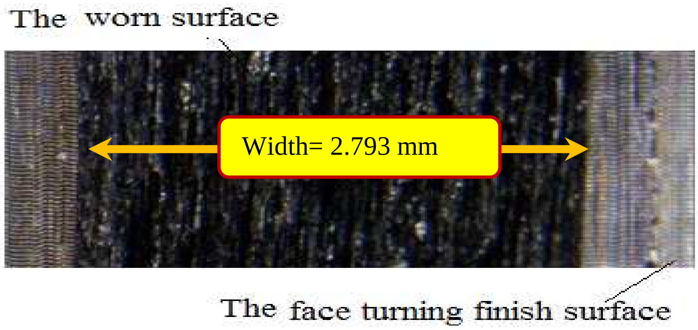
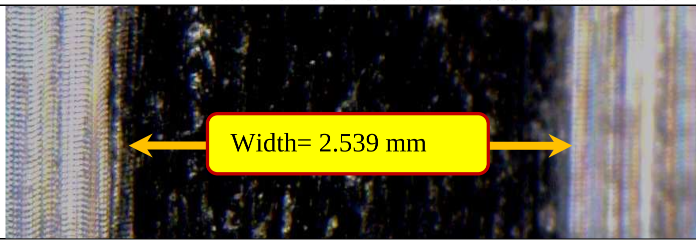
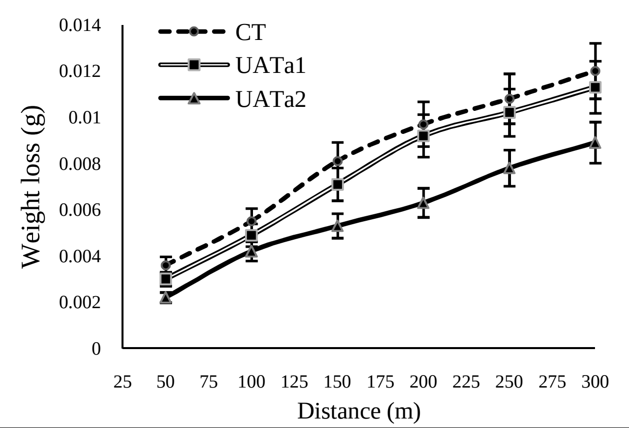
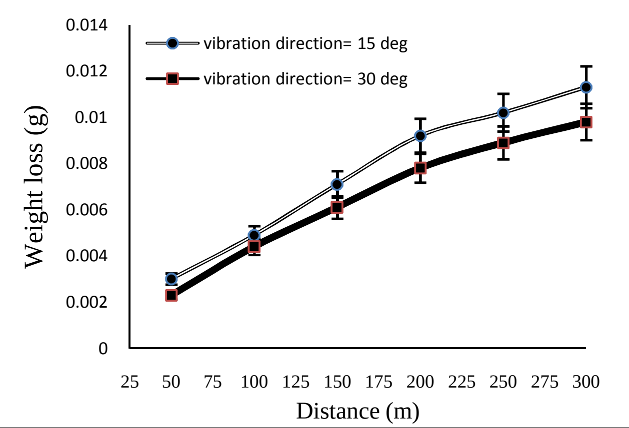
(a)	
(b)	
(c)	

Figure6. Morphologies of wear scars of three kinds of un-textured surface and textured surfaces according to the condition of V_c= 35 m/min, f= 0.205 mm/rev and UAT_{d1}, after the distance of 300 m at the velocity of 0.2 m/s; (a) CT, (b) UAT_{a1}, (c) UAT_{a2}.

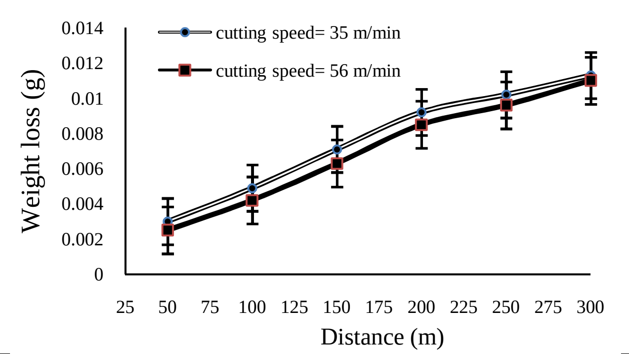
The weight loss of the worn textured and un-textured surfaces is shown in Figure. 7 (a)-(d). It is obvious that wear rates have decreased versus the distance for both of the textured and un-textured samples. Under the same friction condition, the wear rates of textured samples are lower than un-textured ones. The wear rates of textured surfacesby the UAT_{a2}havethe smallest values. Also, increasingthevibration direction and feed resultsin thereduction ofwear in UAT specimens. While increasing of cutting speed leads to the greater values of wear. As discussed before, by increasing of the vibration amplitude, vibration direction and feed, the surface hardness increased. Increasingof the surface hardness leads to the reduction offriction and wear.



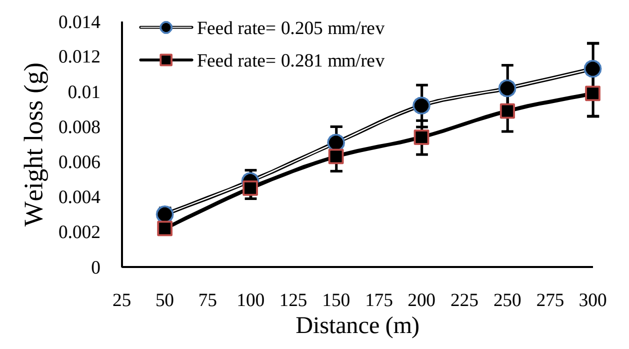
(a) V_c= 35 m/min; f = 0.205 mm/rev; UAT $_{d2}$



(b) V_c= 35 m/min; f = 0.205 mm/rev; UAT_{a1}



(c) UAT_{a1}; f = 0.205 mm/rev; UAT $_{d2}$



(d) UAT_{a1}; V_c= 35 m/min; UAT $_{d2}$

Figure7. Weight loss of the worn sample's surfaces ;(a) vibration amplitude, (b) vibration direction, (c) cutting speed, (d) feed.

4. Conclusions

In this paper, textured surfaces by the UAT process and un-textured surfaces by the CT process were generated.The effects of UAT parameters were studied on the behavior of friction and wear resistance of the Al7075-T6. Conclusions can be summarized as follows:

1- The unique nature of the UAT process in creating micro-dimples on the surface improved surface geometric properties. Increasing of the vibration direction and vibration amplitude in the cutting direction increased the depth of dimples. The formation of micro dimples increased the surface hardness. These factors led to more wear resistance and smaller coefficients of friction.

2- Vibration amplitude (56.75%) had the largest effect on the average coefficient of friction. The parameters of cutting speed (30.43%) and vibration direction (6.07%) were the other influential factors.

3- The average friction coefficients of the UAT_{a1} and UAT_{a2} specimens decreased by 10% and 15%, compared to CT specimens, respectively.

4- Results showed the vibration direction of 0° had the largest values of the average friction coefficient. Hence, the application of fixtures with the angles of 15° and 30°reduced the average friction coefficient moderately by 5% and 8% compared to the fixture with the angle of0°, respectively.

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