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An Investigation into the Effect of Coolants' Concentration and Cutting Conditions on the Coefficient of Friction during Turning of Aluminum 6082-T6

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Abstract –**The general aim of the work in this paper was to investigate the contact conditions at the tool-chip interface when machining aluminium alloy with tungsten inserts during wet machining conditions. Based on the previous work carried out on developing tribometers that can simulate friction during cutting processes, a new tribometer was developed, designed and manufactured for this study. Experimental testing work was carried out on aluminum 6082-T6 tubular specimens. In the experimentation, five different velocities, five loads and five coolant-oil content percentages were used to evaluate the friction with these parameters. The friction tests were performed using a traditional lathe machine to apply suitable speeds used normally in real machining processes. The results are presented with possible explanations for friction behavior.**

Index Terms— **Friction, coolant, cutting conditions, turning.**

I. INTRODUCTION

Friction at the contact in the tool-chip interface generates high heat and influences the tool wear rate. One of the ways of controlling its magnitude is by applying coolants. Even when considering the current trend towards research into minimum quantity lubrication processes, in many cases a flood of liquid is still directed over the tool with the aim of preventing the tool and workpiece from overheating, increasing tool life, and improving surface finish. Selecting a suitable fluid for a particular application among the large number of commercially available fluids is an issue, and a significant challenge due to the fact it is often an empirical process. Today, metal cutting or machine tools form the basis of our industry and are used directly or indirectly in the manufacture of all the products of modern civilization. The value of the world's machine tool production in 2010 reached around 50 billion euro [1].

In machining processes, when the cutting process removes unwanted material from the surface of a raw material that needs to be changed to a desired shape for a certain application, the cutting tool is the most important part in this operation. Much of the research in machining involves dynamics, in particular those of the cutting tool, where the research has investigated related problems such as chatter which is one of the most serious problems in machining operations. Chatter vibration has been investigated for more than a millennium and it is still a significant trouble in achieving automation for most of the machining processes such as turning, milling and drilling [2]. Research into cutting tools is not limited to dynamics as the life of the cutting tool is a very important factor in the discussion of the consumption, productivity, profit and benefits of this process. In addition, the quality of the produced component in terms of roughness and dimensional accuracy is related to the conditions of the cutting tool in terms of sharpness and wear. Consequently, there is a great need to discuss how to improve the contact conditions around the cutting tool in order to extend its life and this improvement can't be achieved unless there is a good understanding and knowledge of the contact conditions that occur at the tool cutting edge. Therefore, a similarly large area of interest involves the tribological interaction that occurs around the tool and chip since tribology is the science that deals with the interaction of components in static contact or relative motion. Thus the study of the contact between the tool cutting edge and chip during machining is at the centre of tribology. The main objectives of this work are to add more knowledge and provide more tools for investigating the tool-chip interface during the metal cutting process.

The main goal of machining is removing material from a workpiece for shaping a new component. Turning is one of the machining processes. In experimental work on machining, turning is the basic operation and the most commonly employed one [3]. Turning is defined as a process of producing a revolved surface by removing the undesired material through the use of a single point cutting edge [4]. Turning as a process of metal cutting is achieved using a machine called the lathe machine by gripping the workpiece by a chuck and holding the cutting tool in tool post and through the relative motion between the rotating workpiece and the fixed cutting tool. Turning is considered a critical process not only because it can remove the unwanted part of materials efficiently, but also because it can create almost all kinds of cylindrical surfaces.

Sliding motion between two bodies which have an interface is only possible if a tangential force is applied. This force is required to shear the junctions and is called the friction force, *F*. The ratio between the friction force and normal load *F/N* is the coefficient of friction, μ. This coefficient varies significantly depending on the materials and processes involved. In metal-forming process, for example, the coefficient of friction ranges from about 0.03 for cold working to 0.7 for hot working, and from 0.5 to as much as 2.0 for machining [5].

In most cases all the frictional energy is converted into heat raising the interface temperature. In other words, the friction generates heat. This temperature may be high enough to soften and even melt the surfaces and, sometimes, to cause micro-structural changes. Excessive temperature lowers the strength, hardness, and wear-resistance of the cutting tool.

The zone of contact between the chip and the tool face is one of the main areas of investigation into the performance of the cutting process. The main controlling conditions in the cutting process are feed, depth of cut, cutting speed and cooling/lubrication medium. A change in value of any of these parameters affect the contact conditions between that chip and tool face and consequently the quality of the produced component and the life of tool. An example of this effect is that the tool life decreases as the cutting force increases and this cutting force can be reduced greatly by the application of a suitable cutting coolant [6]. One of the scales which can be used to characterize the tool-chip interface is friction coefficient. The friction between chip and tool face gives good information about the behavior of this interface. The friction force which is a function of the applied load can give an idea of the degree of the stress caused by the chip on the cutting tool if the contact area is figured out. Friction, wear and lubrication behavior depend on the surface of the material, the shape of the surface and the influence of the operating environment [7].

The friction at the chip-tool interface influences directly the temperature. The actual pressure which occurs during the real cutting process reaches values of around 2 GPa [3, 8]. Many efforts have been done to measure cutting tool friction using different techniques and experimental set-ups.

The methods of friction measurement vary widely. In general, a method that can measure the normal load and tangential force at the real time during sliding can be used to determine the coefficient of friction. By applying this idea, methods such as using a weight hanging on a pulley, the slope of an inclined plane, the deflection of a pendulum, and using piezo-electric crystals or electrical capacity methods are all used for friction measurement.

II. TEST PLATFORM

A. *Test Specimens*

The target material employed to carry out the tests is aluminum alloy 6082-T6 and its chemical composition (wt. per cent) is shown in Table 1.

Table 1 Chemical Composition of Al. 6082-T6 [9]

Comp.	Fe	Si	Mn	Mg	Cu	Cr	Ti	Zn	Al.
%	0.3	1	0.6	0.9	0.1	0.15	0.1	0.1	96.25

The investigated workpiece specimens are tubular in geometry with dimensions of 6 mm thickness, 100 mm diameter and 130 mm. This length was chosen so that the samples could be securely mounted in the chuck of a lathe, with 100 mm of the workpiece protruding for testing. With a protruding length of 100 mm, the workpiece was found to be stable, and not subject to static deflection or vibration for any of the investigation parameters investigated in this study. The geometry used is tubular in order to apply the pin-on-disc friction test technique. The average roughness (Ra) of the workpiece at the contact surface is 0.87 µm.

B. *Testing Rig*

A schematic diagram showing a view of the experimental set-up is shown in Figure 1. The rig contains the main components of testing; the friction pin, pneumatic cylinder, cutting insert and the testing specimen under investigation. The use of the rig and experimental procedure will be described below. The main part in pin-on-disc tribometers is the pin. Nowadays, tungsten carbide inserts are used widely in cutting processes because of their good properties in cutting, such as their ability to resist deformation at high temperatures. This property allow the tungsten carbide inserts to achieve higher metal removal rates compared with HSS tools [3]. In addition, the tungsten carbide tools retain good hardness levels at temperatures of around 1200 ^{o}C [10].

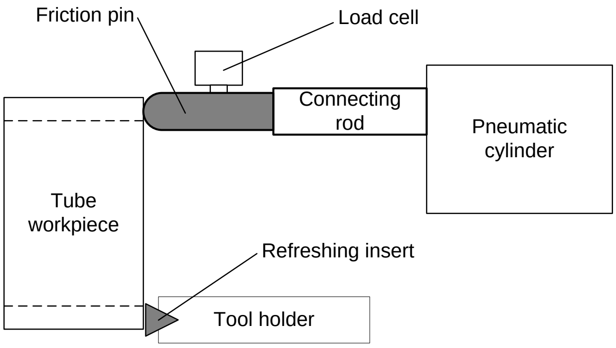

Figure 1: Schematic diagram of friction testing set-up

Therefore, to simulate the friction between this kind of material and the workpiece, a tungsten carbide pin has been manufactured and used in this rig. A cylindrical bar with hemisphere ended shape is the geometry of the friction pin which has been chosen to provide a sufficient contact pressure very similar to the actual contact pressure which is produced between the cutting tool and the workpiece. A full pin has a spherical end with diameter of 14 mm and a length of 30 mm.

III. EXPERIMENTAL METHODOLOGY

A. Testing Procedure

The examined workpiece material is fixed directly on the lathe's chuck where it is rotated according to the spindle speeds of the machine. The tribometer rig is mounted by fixed bolts on the tool post of the machine where it can be moved in two axes. One is parallel to the face of the cylinder. The movement in this direction is controlled manually using a dial gauge to make sure that the centre of the friction pin is at the middle of the rotating face of the workpiece. The adjustment to locate the pin at this position is done once the specimen is changed. The second direction of movement is perpendicular to the face of the workpiece. This movement is controlled automatically according to the movement of the lathe mechanism. During this movement the friction testing and machining of the face take place. The testing procedure is done as described below.

The friction tests take place using a traditional lathe machine of trade mark XYZ 1600 to apply suitable speeds used normally in real machining processes. The workpiece rotates anticlockwise at speeds which vary according to the investigation conditions. The coolant is applied after its concentration is checked using a refractometer. The desired pressure of compressed air which is needed to apply the aimed load is controlled using a pneumatic hand valve and a digital pressure gauge. Once this pressure reaches the desired value, the friction test starts by engaging the automatic mechanism of the lathe machine and applying the compressed air on the pneumatic cylinder which pushes the friction pin in a direction normal to the face of the rotated workpiece. Owing to the rotation of the workpiece, the pressed friction pin is pushed up, creating a force on the load cell. The worn surface of the rotating face of the investigated aluminum cylinder needs to be removed and refreshed during the testing process, since that is exactly what occurs during the machining process. A special tool holder is designed and manufactured to be fitted at a right angle with the face of the investigated disc, so the cutting insert removes the worn surface due to the deformation caused by the pressed pin at one pass instantly. In order to achieve a good finished surface and refreshed surface in one pass of cutting, the insert of square shape with cutting edge of 8 mm was chosen, which is appropriate to the thickness of the workpiece tube. That is to make sure the friction tests take place on a new refreshed surface every time and the pin does not go into the same track again.

The load cell measures the amount of friction force and sends a signal according to this value to the PC through a program designed for this experimental work under the LabView package. The program records any change in friction force, divides this force by the normal applied load and plots a graph showing the profile of the friction coefficient. This process of testing and measurement is repeated three times for each run. The duration of each test is 60 seconds even though the test can be run for up to 10 minutes. In a 60 seconds period the friction pin runs for a sliding distance of around 140 m. The friction pin is re-polished after each run and the workpiece's face is refreshed at the same time, using the cutting insert mentioned previously, according to the designed mechanism of the tribometer.

B. Testing conditions

Five different velocities, five loads and five coolant oil content percentages were used to evaluate the friction rate. The test conditions of the friction tests are shown in Table 2.

Table 2: Test conditions

Load N	200	300	400	500	600
Speed m/min	30	60	90	120	150
Coolant concentration %	4	8	12	16	20

As previously discussed, cutting fluids are widely used to reduce friction and wear, as well as to provide cooling. In this study, the cutting fluid was mineral-oil based, with a performance additive content of 20%, the performance additive was phosphorus. The additives used to provide improvements in extreme pressure performance. The wetting is maintained at 42 dynes/cm. More details are shown in Table 3.

In general, cutting coolant concentrations are between 1% and 20% in water [11]. In this work the tests are done under lubricated conditions by using machining coolant at a range of concentrations.

Table 3: Fluids' specifications [12]

Viscosity cP	Mineral oil content (mass %)	Performance additive (mass %)	E.P additive (Type)	Wetting (Dynes/cm
308	50	20	Phosphorus	42

C. Design of experiments

Traditional experimentation involves considerable effort and time, particularly when a wide range of investigation work is needed. Design of experiments is a very efficient method for developing valuable research while saving time in the process. Generally, when the experimenter [13] plans his experiments, he achieves results in a much more economical manner. As a rule, an experiment designed to find the optimum conditions of a process is described adequately by a second order polynomial.

The technique used in this study for designing experiments was introduced by Box and Hunter [13] . A rotatable factorial design of experiments with a central composite of second order (2^k) can be used to enhance the reliability of investigation work. In addition, the number of runs of this process is reduced with increased accuracy. It should be noted here, that k is the number of factors involved in the process.

Experimental work involves the study of the relationships between different factors at different levels and a certain response and this is where the design of experiments technique is helpful.

The package of design of experiments and analysis of variance used in this study has been used widely in experimentation work [13-17]. The spherical variance function designs are preferable since these designs provide a constant variance for the response at all points of the experiment since they are at the same radius from the centre of the design. These kinds of designs are known as rotatable designs.

Suppose that we have k variables $x_1, x_2, \dots \dots x_k$ and we want to fit them to a polynomial of degree $d = 1$, the simplest surface is then a plane given by

$y = b_o + b_1x_1 + b_2 + \cdots \dots . + b_kx_k$

where, b_o is the free coefficient.

As a rule, the experiment designed to find the optimum conditions of the process is described adequately by a second-order polynomial [18]. For this polynomial, the number N of observations included in the design should not be less than the number of estimated coefficients of the second-order equation for k factors. The investigated variables are coolant concentration, speed and applied load, so the k are three.

The mentioned factorial design was used (in this study k=3). The total number of experiments will be 20 which include 8 corner points $(n_c - 2^k)$ at ± 1 level, 6 axial points $n_a = 2k$ at ± 1.682 and 6 repeated runs at zero level as centre points (n_a) to evaluate the pure error

IV. RESULTS

The results obtained, based directly on the designed matrix of experiments, are for the coefficient of friction and are plotted in Figure 2. It is should be noted here that the average of each three recorded values is measured and plotted on the figure. From an initial look at the figure, it is clear that the increase in oil content from 8% to 16% causes a decrease in the friction coefficient as shown for runs 1 and 2, 3 and 4, 5 and 6, and 7 and 8. On the other hand, the highest friction coefficient is recorded at run 9, where the oil content in the coolant is the least at 4%.

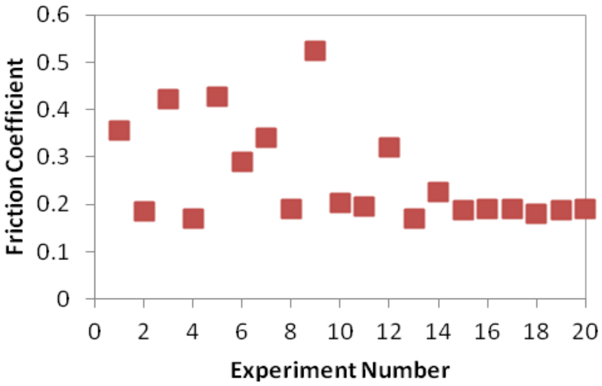

Figure 2: Experiments' results

A. Analysis of Variance

As part of the design of experiments, the regression coefficients are calculated.

The results are tested statistically using the ANOVA technique. The F-ratio test as a tool of the analysis of variance is used to check the adequacy of the model. To determine whether the final equations are a good fit to the experimental observations, the F-ratio test is carried out. It should be noted that the equation fits the experimental data, if the computed F-ratio of both first and second terms are larger than the standard value of the F-ratio whereas the computed F-ratio of lack of fit must be smaller than the standard value [13] of the F-ratio for a significance level $\alpha = 0.5$, 3 and 5 degrees of freedom is; $F_{0.5,(3,5)} = 5.41$, degree of freedom 5 and 5 is; $F_{0.5,(5,5)} = 5.05$ and at degree of freedom 6 and 5 is; $F_{0.5,(6,5)} = 4.95$.

The calculated values of first and second order coefficients are greater than those of the standard F-ratio; furthermore the lack of fit is smaller than that given by the standard F-ratio. Hence, the regression equations which have been derived are in agreement with the experimental results observed. After the testing of the regression coefficients by F-ratio, the friction coefficient can be derived as an empirical equation as follows:

$$\mu = 0.188 - 0.092x_1 + 0.005x_2 + 0.015x_3 + 0.066x_1^2 + 0.029x_2^2 + 0.007x_3^2 + 0.012x_1x_2 + 0.017x_1x_2 - 0.03x_2x_3$$

B. Effect of coolant concentration and cutting speed on coefficient of friction

The coefficient of friction is found and can be used to investigate the behavior of friction according to the conditions chosen for this test. The relationship between friction coefficient, coolant-oil content and sliding speed using the coolant is shown in Figure 3 .

From the graph, the lowest actual coefficient of friction found is 0.05, at a coolant concentration of 16% and a sliding speed of 90 m/min, whereas, the highest actual coefficient of friction found is 0.6, at a coolant concentration of 4% and a sliding speed of 150 m/min.

It can be seen how the friction coefficient decreases at all speeds used as the oil concentration increases to 12%. As the speed passes 90 m/min the friction starts to increase at all concentrations except when the concentration is 20%. As the coolant concentration passes 16% there is little change in the friction coefficient

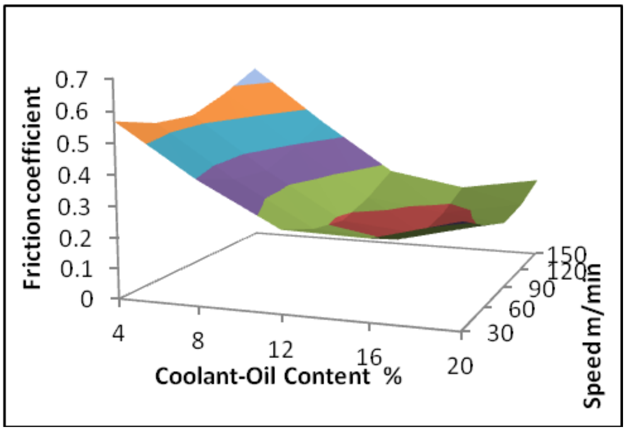

Figure 3: Effect of coolant concentration and cutting speed on friction coefficient

C. *Effect of coolant concentration and load on actual coefficient of friction*

The relationship between friction coefficient, coolant-oil content and the applied load on the friction tool is shown in Figure 4. The graph shows that the friction coefficient drops rapidly as the coolant concentration increases from 4% to 12% and remains steady at between 16% and 20%. The coefficient of friction decreases as the load increases for coolant concentrations of 4%, 8% and 12% at low loads up to 400N, then as the load increases the friction coefficient increases for almost all concentrations. However, when the coolants concentration is 8% the increase in friction coefficient is not significant.

The highest coefficient of friction is 0.5, at a load of 200N and a coolant concentration of only 4%, whereas the lowest value of friction is around 0.1 at oil content percentages of 16% and 20% under low loads of 200 and 300N.

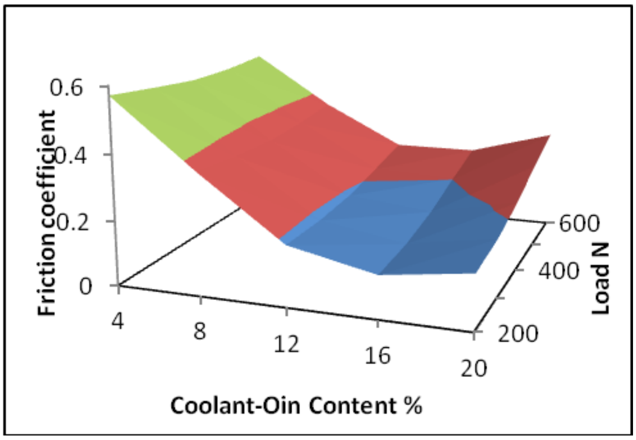

Figure 4: Effect of coolant concentration and load on actual coefficient of friction

V. DISCUSSION

A. *Oil Content and Speed*

The influence of the change in sliding speed and the coolant’s oil content can be discussed on the basis of the graph presented in Figure 3. It can generally be seen from this graph that there is a significant decrease in friction coefficient with an increase in oil content from 4% to 12% at any speed. This may be due to the slippery environment provided by the oil. With oil content between 16% and 20% the friction coefficient does not change much.

The increase in coefficient of friction due to the increase in speed over 90 m/min may be related to the heat generated between the friction pin and the workpiece. As the pin goes faster it starts becoming hotter at the surface. With the increase in heat the viscosity of the oil decreases and this probably leads to a reduction in the capability of the coolant to a reduce friction.

The pin acts like bearing, since the fluid film is generated due to the relative motion between pin and the plate. This motion drags the coolant in to what is called the wedge area. As the speed increases, more coolant is dragged into the pin-plate interface and hence coefficient of friction is reduced. As the speed gets higher, a heat is generated and water evaporates leaving the oil viscous and not being dragged easily, so no benefit of adding more and more oil. That may be the reason behind the increase in coefficient of friction at higher speeds. However, an increase in speed at higher values increases the friction coefficient may be also because of the difficulty of penetrating due to the centrifugal force, even though the friction coefficient is still lower at higher values of oil content.

B. *Oil Content and Load*

The effect of oil content on the actual friction coefficient at different loads can be assessed from Figure 4. It can generally be seen from these figures that the friction coefficient decreases with an increase in oil content at any value of load. This may be due to the slippery environment provided by the oil. The lowest friction coefficient obtained using the three coolants in this study, was from coolant A. However, an increase in loads at higher values increases the friction coefficient, may be because of the difficulty of penetrating due to the high contact between pin and workpiece, even though the friction coefficient is still lower at higher values of oil content. This means that there is a good relationship between oil content in the coolant and load and the oil content percentage is a significant factor. An increase or decrease in coefficient of friction in machining is due to the change in cutting forces and that is why the friction coefficient goes up as loads increase. It was found that the decease in cutting force must come from the reduction in effective friction at the tool-chip interface [19] and the cutting force is found to depend strongly on the coefficient of friction [20].

VI. CONCLUSIONS AND RECOMMENDATIONS

The developed tribometer was used to find the actual coefficient of friction. On the basis of the use of this tribometer, the influence of coolant type and concentration under different conditions of load and speed were investigated. From the experiments performed the following results are drawn:

1- The results showed that the coefficient of friction is influenced by the mentioned conditions and the tribometer can be used to investigate the effect of the machining conditions and cutting fluids on the coefficient of friction.

2- This set of experiments is implemented using the Box and Hunter technique for the design of experiments as described above. This technique is used to see the variation of different conditions and their interaction; in addition, it provides the possibility of mapping a broad solution space in an accurate manner, which otherwise would not be realistically achievable.

3- The relationship between the friction coefficient and experimental conditions (coolant-oil content, speed and load) was adapted into polynomial response equation of second-order for the response.

4- It can generally be seen from the results that there is a significant decrease in friction coefficient with an increase in oil content from 4% to 12% at any speed and by the same way the friction coefficient decreases with an increase in oil content at any value of load.

5- At speeds higher than 90 m/min the friction coefficient starts to increase at almost all oil content rates. The increase in loads increases the friction coefficient too. However, the influence on friction coefficient due to the change in oil content and speed is more significant than it due the change in load.

REFERENCES

1. CECIMO (2011) *Study on Competitiveness of the European Machine Tool Industry*.
2. Siddhpura, M. and R. Paurobally, *A review of chatter vibration research in turning.* International Journal of Machine Tools and Manufacture, 2012. **61**(0): p. 27-47.
3. Trent, E.M. and P.K. Wright, *Metal cutting*. 4th ed. 2000, Oxford Butterworth-Heinemann.
4. Shaw, M.C.M.C., ed. *Metal cutting principles*. 1989, Clarendon Press: Oxford
5. Kalpakjian, S. and S.R. Schmid, eds. *Manufacturing engineering & technology*. 5th ed ed., Harlow : Prentice Hall, 2006.
6. Williams, J.A. and D. Tabor, *The role of lubricants in machining.* Wear, 1977. **43**(3): p. 275-292.
7. Bhushan, B., *Principles and Applications of Tribology*. 2013, Wiley.
8. Buryta, D., R. Sowerby, and I. Yellowley, *Stress distributions on the rake face during orthogonal machining.* International Journal of Machine Tools and Manufacture, 1994. **34**(5): p. 721-739.
9. Direct Plastics, *Aluminium 6082-T6 Data Sheet* 2011, Direct Plastics Limited: Sheffield, UK.
10. Beddoes, J. and M.J. Bibby, *Principles of metal Maufacturing Processes*. 2003, Carleton University, Canada.
11. Gunter, K.L. and J.W. Sutherland, *An experimental investigation into the effect of process conditions on the mass concentration of cutting fluid mist in turning.* Journal of Cleaner Production, 1999. **7**(5): p. 341-350.
12. Houghton, *Cutting Fluids Data Sheet*. 2012, Houghton Manchester, UK.
13. Box, G.E.P. and J.S. Hunter, *Multi-Factor Experimental Designs for Exploring Response Surfaces.* The Annals of Mathematical Statistics, 1957. **28**(1): p. 195-241.
14. Allus, M.A., R.G. Brereton, and G. Nickless, *The use of experimental design, multilinear regression, ANOVA, confidence bands and leverage in a study of the influence of metals on the growth of barley seedlings.* Chemometrics and Intelligent Laboratory Systems, 1989. **6**(1): p. 65-80.
15. El-Axir, M.H., O.M. Othman, and A.M. Abodiena, *Study on the inner surface finishing of aluminum alloy 2014 by ball burnishing process.* Journal of Materials Processing Technology, 2008. **202**(1–3): p. 435-442.
16. El-Axir, M.H., O.M. Othman, and A.M. Abodiena, *Improvements in out-of-roundness and microhardness of inner surfaces by internal ball burnishing process.* Journal of Materials Processing Technology, 2008. **196**(1–3): p. 120-128.
17. Wardrop, D.M. and R.H. Myers, *Some response surface designs for finding optimal conditions.* Journal of Statistical Planning and Inference, 1990. **25**(1): p. 7-28.
18. Joyce, R.M., *Experiment optimization in chemistry and chemical engineering, S. Akhnazarova and V. Kafarov, Mir Publishers, Moscow and Chicago, 1982, 312 pp. Price: $9.95.* Journal of Polymer Science: Polymer Letters Edition, 1984. **22**(6): p. 372-372.
19. Marusich, T.D. *EFFECTS OF FRICTION AND CUTTING SPEED ON CUTTING FORCE*. in *Proceedings of ASME Congress 2001*. 2001. New York, NY.
20. Shi, G., X. Deng, and C. Shet, *A finite element study of the effect of friction in orthogonal metal cutting.* Finite Elements in Analysis and Design, 2002. **38**(9): p. 863-883.

Biographies

Abdulaziz Abodena was born in 1965. He received BSc. degree in mechanical engineering from Benghazi University in 1988, Master in production engineering from Tripoli University and PhD in mechanical from the University of Sheffield. He is currently lecturer in department of mechanical and industrial engineering at faculty of engineering in Gharyan city.