The Effect of Artificial Aging Treatment and Lubrication Modes on the Cutting Force and the Chip Surface Morphology when Drilling Al-Si-Mg (A356) Cast Alloys

Keyhan Jabbari[1], Seyed Ali Niknam[1]*
[1]School of Mechanical Engineering, Iran University of Science and Technology
*Email of Corresponding Author: saniknam@iust.ac.ir
Received: August 24, 2018; Accepted: October 10, 2018

Abstract
This article reports the effects of various artificial aging methods and lubrication modes (dry, mist, wet) on the recorded cutting forces and chip morphology in drilling Al-Si-Mg (A356) cast alloys. In the course of this work, the work part sampled were as-received alloy (T0), solution heat-treated alloy (SHT) and then aged alloys at 155°C, 180°C, and 220°C (T4, T6, T61, T7), respectively. The significant effects of artificial aging the recorded cutting forces were noticed. Except minor cases under lower levels of feed rate, in general lower cutting forces were observed in A356-T0 and A356-T7 which are more brittle than other tested alloys. A direct relationship can be formulated among the microcracks on the free surfaces of the chips, brittleness and the recorded cutting forces. The use of MQL led to lower resulting cutting forces under similar cutting conditions. This can be related to less effect of thermo-mechanical stresses on the work part under MQL mode which tends to reduce the cutting forces.

Keywords
Aluminum Alloys, Heat Treatment, Artificial Aging, Surface Quality, Cutting Force

1. Introduction

The A356 aluminum alloy comes from the Al-Si-Mg family which is grouped as a heat-treatable alloy due to the presence of magnesium content, which combines with Si to form the Mg_2Si precipitation hardening phase [1]. Such alloys are subjected to solution heat treatment at temperatures close to the eutectic temperature, in order to obtain the maximum amount of Mg and Si in solid solution, as well as avoid localized melting at the grain boundaries [2, 3]. The solution heat treatment of AA 356 has been widely used in the automotive industry for fabrication of several types of automobile parts, such as wheels, panels and even in the vehicle structure. Using these alloys as an alternative to steels is expected to lead to great improvements in energy savings, recyclability and life-cycle cost.

Heating the solution heat treated alloys to above roomtemperature and sustaining the similar conditions for a specific period of time may lead to increased precipitation rate and the strength comparing to natural aging used. The abovementioned process is known as artificial aging, age hardening or just aging that is generally carried out at temperature up to approximately 150^{o}C for Al-Si-Mg alloys [4]. In fact, it is to note that the aging treatments are used to precipitate out the alloying elements which were originally placed and kept in solid solution by the solutionizing and quenching processes. The role of heat treatment in the machinability of the common alloys has been

extensively reported in the literature [5-8]. Heat treatment increases the hardness, while it also reduces the presence of built-up-edge (BUE) formation on the cutting tool and tends to improve the surface finish of the machined part. Knowing that higher cutting loads and temperatures appeared at the higher hardness, it can be exhibited that detrimental effects on the tool life are expected when the hardness of the workpiece increases. In drilling and turning operations, any increase in the cutting temperature is unfavorable to tool life since it produces excessive accelerated heat-causing wear-out of the edge. In milling operation, the increased hardness leads to higher impact loads when the inserts experience the interaction with the work part in cutting operations, often resulting in the premature breakdown of the cutting edge [9]. Typical automotive machining techniques, however, usually require a minimum of workpiece' shardness in order to avoid potential complications associated with built-up edge (BUE) occurrence. Most automotive machine shops agree that a minimum hardness of 80BHN is desirable [10, 11]. As a courtesy to this observation, the 319 aluminum alloy intake manifolds are often aged to the T5 temper, and the 356 aluminum alloy manifolds usually require full heat treatment to the T6 temper [5, 12].
Knowing that the hardened material is associated with higher cutting force and cutting temperature, the use of lubricated machining might be demanded, in particular when higher machining efficiency and better surface quality are required under severe cutting conditions. In fact, despite the benefits aforementioned, the use of cutting fluids degrades the environment and increases the machining cost around 16-20% of production costs. To overcome the restrictions imposed against lubricated machining, special attention has been paid to use of dry machining over the past few years. However, since few years ago, a new technique known as minimum quantity of lubricant (MQL) [13] has been proposed to insert the fluid/lubricant in atomized format through a nozzle to form fine droplets which are fed to the machining area in the form of an aerosol spray at a rate not exceeding 100 ml/h [14]. The successful applications of MQL and cryogenic in drilling operations are reported in literature [15-18]. Sreejith and Ngoi [19] reported the effects of dry, MQL, and flooded coolant conditions on cutting forces, surface roughness and tool wear in turning aluminium alloy. It was found that when properly employed, MQL can replace the flooded coolant condition. According to review of literature, limited studies are available about the effects of artificial aging methods on machinability attributes of A356 under various lubrication conditions [20]. Therefore, the main objective of this study is to evaluate the influence of machining conditions and cutting fluid on the cutting force and the surface roughness attributes in drilling A356 aluminum alloys under several heat treatment conditions and lubrication modes. To better study the effects of heat treatment methods on machinability attributes, the machined parts were heat-treated to produce different precipitation states and were then machined under controlled cutting conditions.

2. Material and Method

2.1 Sample preparation

The basic requirements of the age-hardening of an alloy system are: decreasing solubility with decreasing temperature, and the formation of clusters of solute atoms coherent with the matrix; in other words, there should be an orientation relationship between the precipitates and the matrix [21]. The greater portion of growth in tensile properties that accompanies most heat treatments is a

result of the formation of non-equilibrium precipitates, such as the θ phase, during the application of the aging treatments. Since the structure and morphology of the precipitates are controlled by the times and temperatures used in the heat-treatment sequences, it is possible for a considerable amount of control to optimize the strength, ductility, and toughness of these alloys. In the precipitation-strengthened alloys, it is possible for more than one phase to be precipitated in the matrix of a predominant phase. To obtain the best results, the precipitate phase should be hard and discontinuous, its particles small and numerous, while the morphology should be rounded rather than sharp-edged. On the other hand, the matrix should be soft and ductile so that if the cracks were to nucleate, it would be much safer for this to take place in the particles than in the matrix [22].
The following heat treatment conditions were performed:

- T0: as-cast condition
- T4: Solution Heat-Treated (SHT)+ Quenching
- $T6_1$: SHT+ Quenching+ Artificial aging at 155°C for 5 hours
- $T6_2$: SHT+ Quenching+ Artificial aging at 180°C for 5 hours
- T7: SHT+ Quenching+ Artificial aging at 220°C for 5 hours

All samples were solution heat-treated at 540˚C, for solution period of 8 hours. The solution-heat treated samples were then quenched in warm water (60˚C). In all abovementioned conditions, the samples were solution heat-treated and quenched at the same time leaving only the other condition, such as natural and artificial aging time.

2.2 Experimental Plan

Experimental works were carried on a high-speed 3-axis CNC milling machine (Power: 50 kW, Speed: 28000 rpm, Torque: 50 Nm) using non-coated high-speed steel twist drills (3/8 inch stub drill bright finish with 118˚ point angle). The three levels of rotational speeds (2000, 6000, 10000 rmp) as well as feed rate (0.015, 0.15 and 0.35 mm/rev) were used. The experimental works were repeated twice and the average of readings was considered.
It is to underline that similar drilling tools were used throughout the tests in order to ensure the uniformity of geometry, microstructure and properties of the tools used. The work materials were rectangular blocks of aluminum 356 cast alloys with 300×100×20 mm in size, mounted on a special machining fixture.
The MQL tests were used with the delivery pressure of 6 bar gauge and flow rate 50 ml/h. The vegetable oil was used as the lubricant. The flow rate under wet mode was 5000 ml/h.
A three-axis table dynamometer (Kistler 9255-B) was used to record the cutting forces. The cutting forces were then amplified and analyzed using the sampling frequency of 48 KHz. The drilling performance was evaluated based on the total drilling cutting force (F_t). The scanning electron microscope (SEM) was used to characterize the tool wear and the chip formation morphologies.

3. Results and Discussion

3.1 Cutting Force

The total drilling cutting force (F_t) under different cutting conditions and lubrication modes are presented in Figures 1-3. Despite the lubrication modes and age hardening methods used, higher cutting forces were observed under higher rotational speed when the lowest level of feed rate is used. This phenomenon can be attributed to the difficulties of adequate plastic deformation at lower levels of feed rate. In fact, in such cutting conditions, the use of low levels of feed rate leads tolonger contacts between the cutting tool and work part. Consequently, heat generation may occur, while in fact no proper cutting action is taken place. In very low levels of feed rate,rubbing takes place rather than cutting process. Consequently, at higher levels of cutting speed, more heat generation and stress is applied to the cutting tool and eventually increased cutting forces may occur. Despite the lubrication mode used, the different trends can be observed at higher levels of feed rate (0.15 and 0.35 mm/rev).

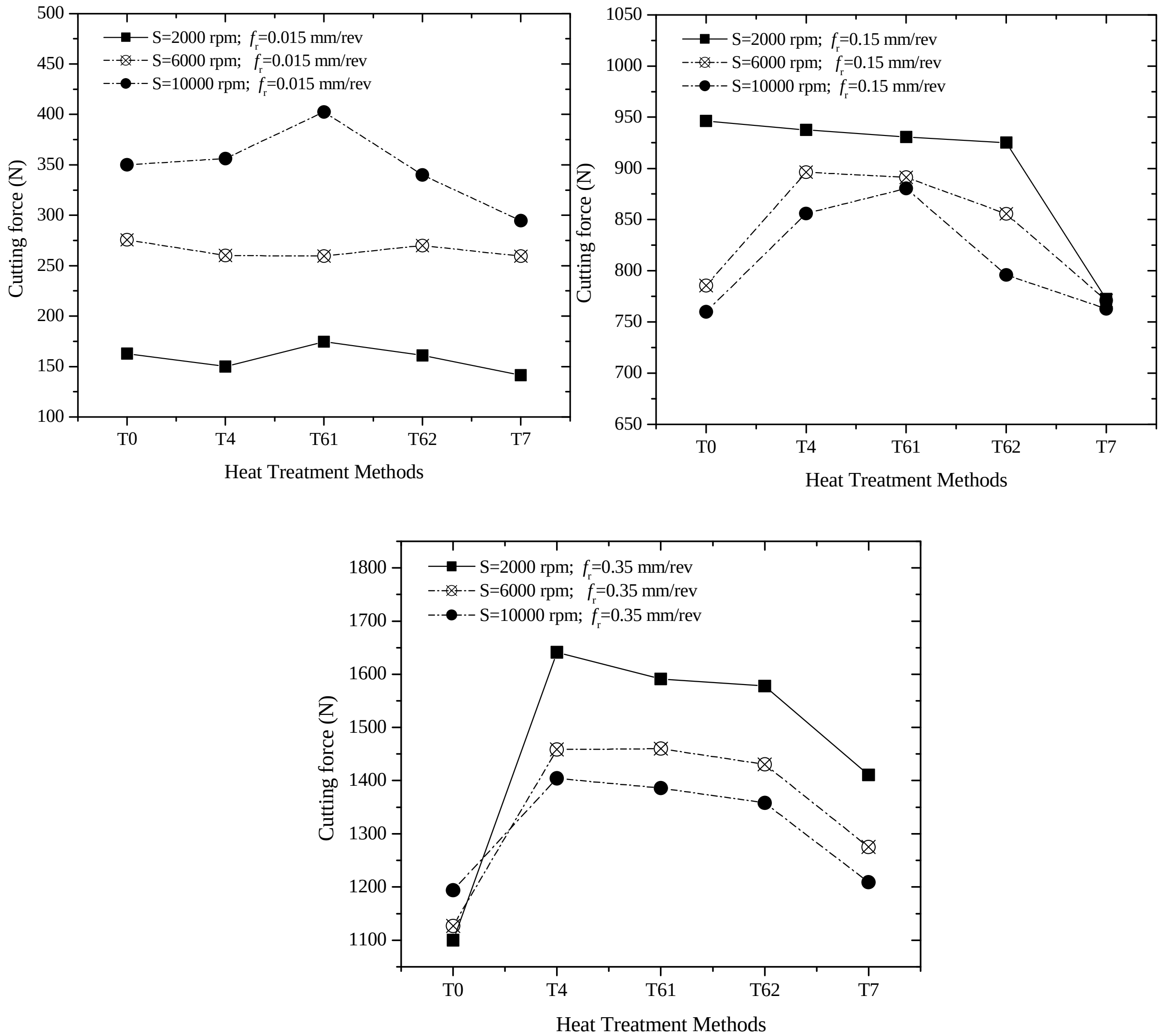


Figure1. The recorded cutting forces under dry lubrication mode

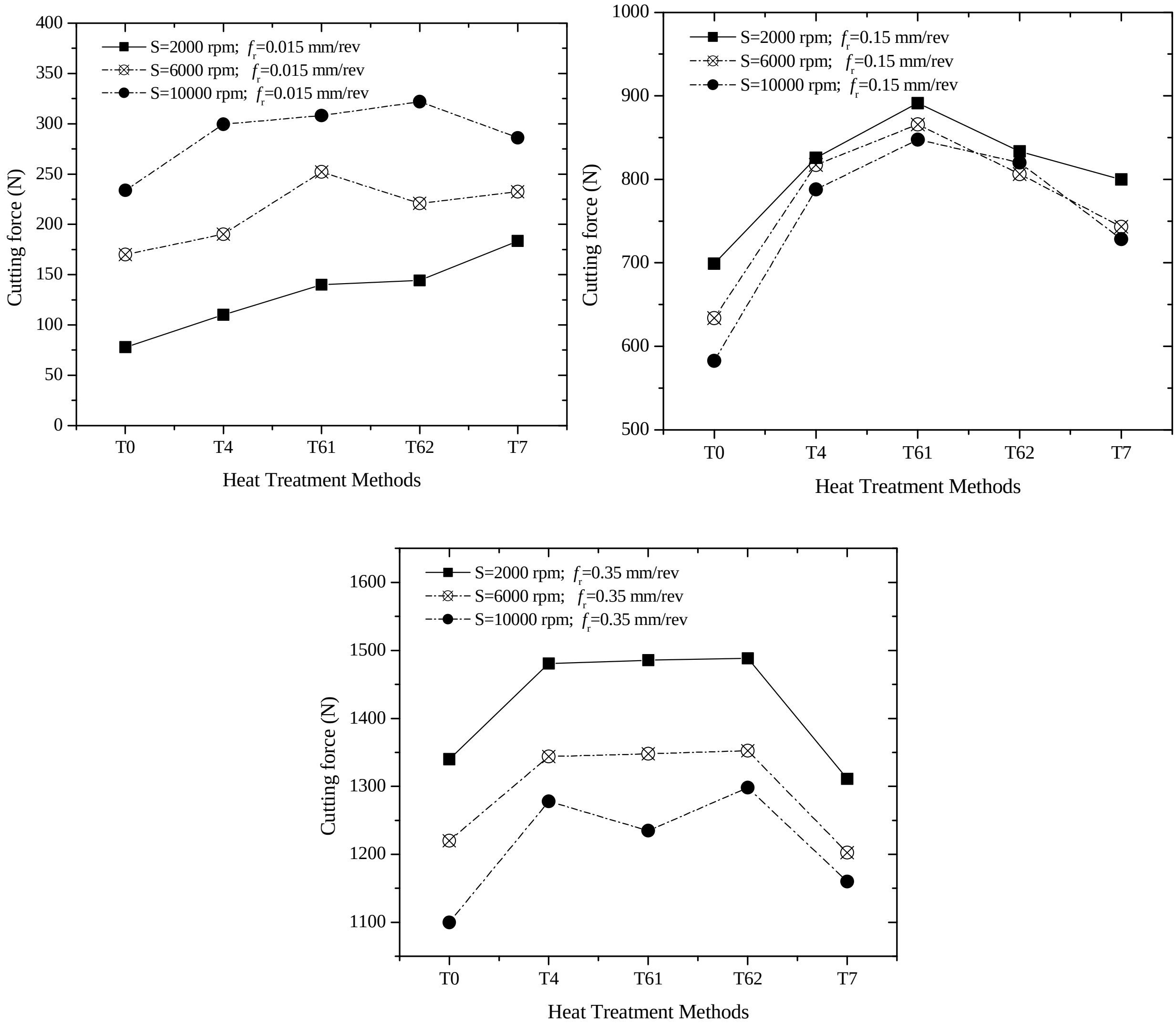


Figure2. The recorded cutting forces under mist lubrication mode

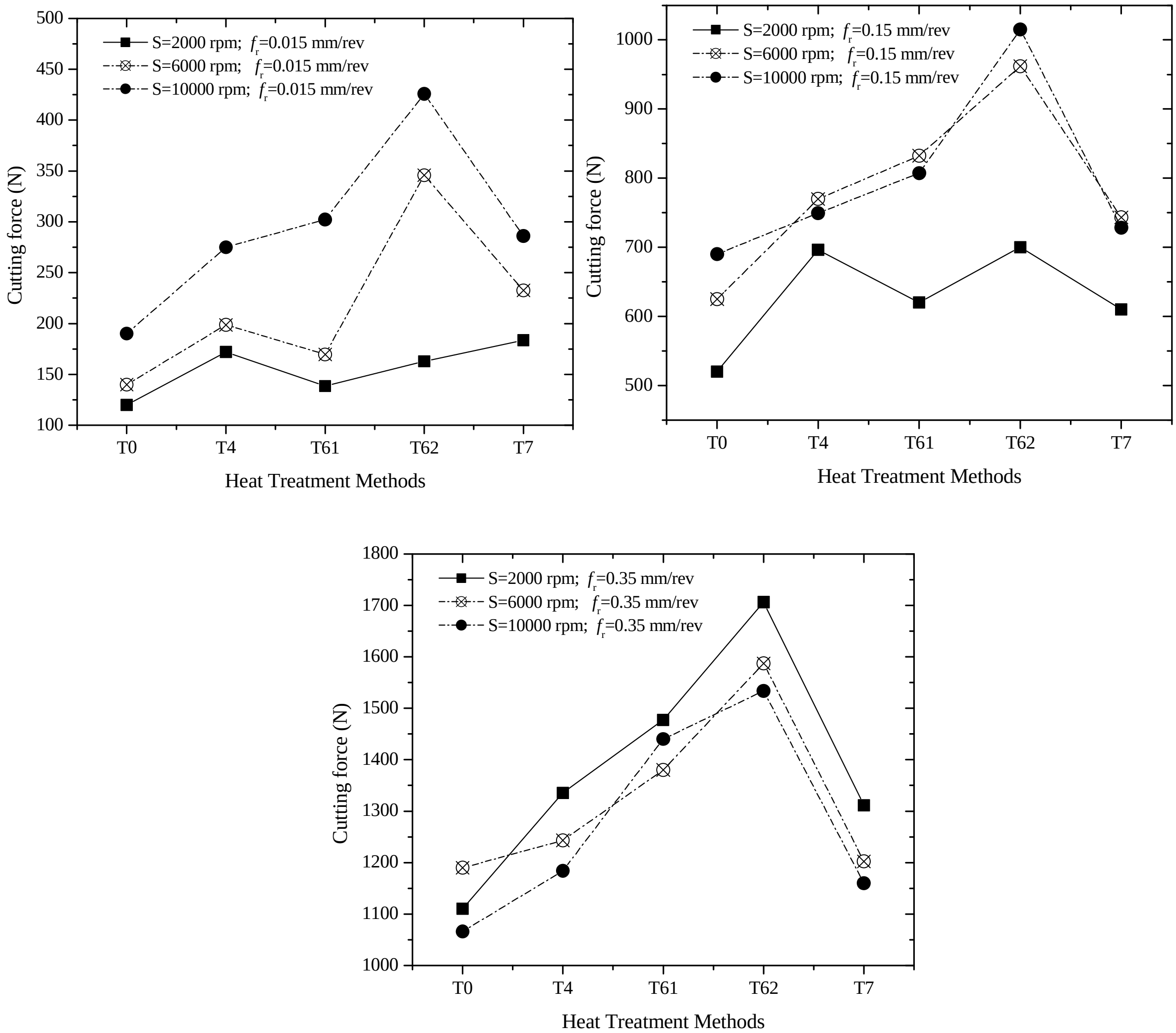
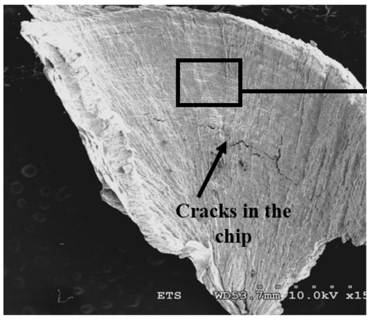


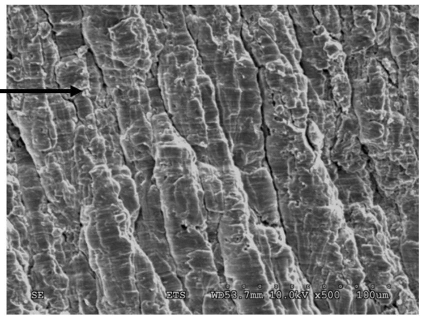
Figure3. The recorded cutting forces under wet lubrication mode

Despite the levels of cutting speed and the feed rate used, increased cutting forces occur on the T4, T61 and T62 work part under wet mode, while contrary, reduced cutting forces were observed under T7. This phenomenon reveals the direct effects of cutting speed and feed rate on the cutting the force. However, as similar as the cutting tests under mist and dry modes, lower cutting forces were observed under T7. It can also be stated that the T7 increases the brittleness feature as compared to other treatment methods with aging. Consequently, except minor cases, despite the lubrication mode and the cutting parameters used, lower resulting values of cutting forces were observed as compared to other heat treatment methods used. Moreover, expect minor cases, despite the age hardening and the cutting parameters used, the lower cutting forces were observed under mist mode. This can be considered as the potential benefit of MQL. Under wet mode, due to thermo-mechanical stresses induced to the work part as a result of rapid cooling and warm-up phenomenon, higher cutting forces were observed. Furthermore, as discussed earlier, the MQL machining is associated with less environmental hazardous effects as well as machining cost.

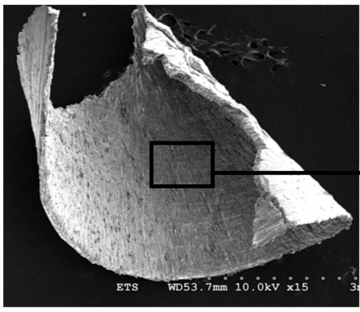
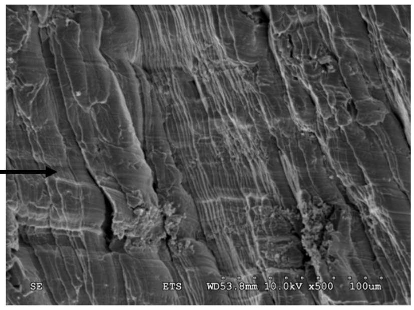
3.2 Chip surface characterization

Figures 4(a) and 4(b) present the SEMimages of drilling chipsrecorded during drilling A356-T0. The outsidesurface of this chip exhibits many small cracks, which is acharacteristic of brittle feature of A356-T0 cast alloys. The deformation and the frictionon this surface are higher than other tested parts. A356-T61 revealsno systematic segmentation behavior. It was observed that thefragmentation bands are denser and strongly crushed againstone another asshown in Figures 4(e) and 4(f), whereas the bands are more separated in the case of over-aging A356-T7 material. Consequently, due to easier plastic deformation and ease of cut in A356-T0 cast alloys, lower resulting values of cutting forces were recorded as compared to other tested parts.In fact, the presence of microcracks in the brittle materials decreasesthe micro-friction and in turn less cutting forces are demanded. This phenomenon confirms the findings in Figures 1-3. In fact, less recorded cutting forces in A356-T0 and A356-T7 despite the lubrication methods used (Figures 1-3) confirm less cutting forces in more brittle materials.The more brittle materials,the more cracks on the chips and the lessdifficulties in the chip formation and plastic deformation processes. Consequently, those materials with higher cracks on the chips can be cut easier and eventually lower resulting values of cutting forces are expected. In fact, the observations made in Figure 4 are align with the findings in Figures 1-3.

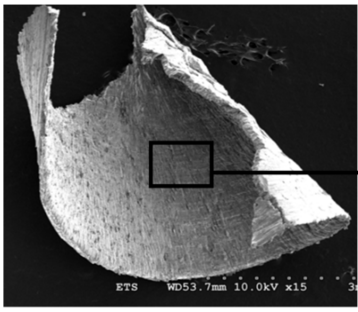
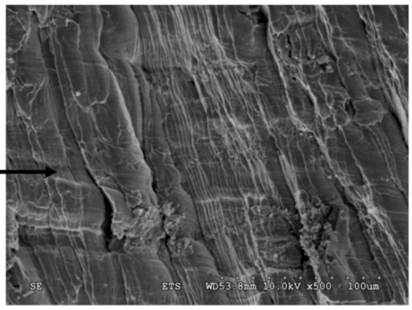




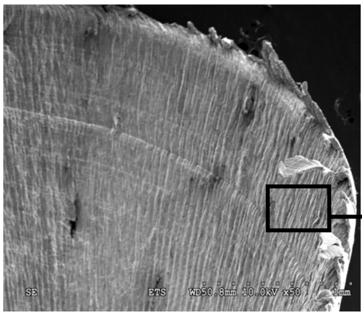
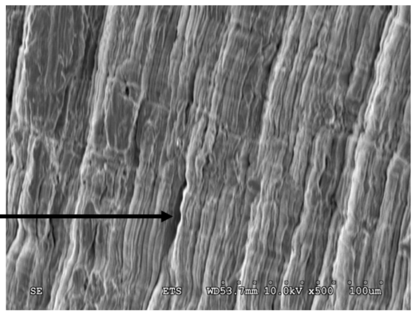
(a) AA 356-T0_ X15 (b) AA 356-T0_ X500

(c) AA 356-T4_ X15 (d) AA 356-T4_ X500

(e) AA 356-T61- X50 (f) AA 356-T61- X500

(g) AA 356-T7- X50 (h) AA 356-T7- X500

Figure4. SEM images of the drilling chips of AA 356 (at different resolutions)under various heat treatments and artificial aging methods

4. Conclusion

- The following conclusions can be presented from experimental works conducted with a view of studying the effects of artificial aging methods on recorded values of cutting force in drilling of A356-T0,A356-T4, A356-T61, A356-T62, and A356-T7 under dry, mist, and wet lubrication modes.

- The experimental results prove that the variation of heat treatment methods has significant effects on the change of cutting forces. Except minor cases as low levels of feed rate, the lowest resulting values of cutting forces were recorded on the A356-T7 and A356-T0, despite the cutting conditions and lubrication methods used. This phenomenon can be related to higher brittleness in the tested parts than others. The chip surface characterization studies led to present direct relationships between the micro cracks on the free surfaces of the chips, brittleness and the recorded cutting forces.
- Except minor cases at the lowest levels of feed rate, the maximum cutting forces were found on the A356-T61, A356-T62, despite the lubrication modes used. This can be related to the induced hardening on the work parts which increases the cutting forces.
- It was observed that despite the feed rate and cutting speed used the use of MQL method led to lower resulting values of cutting forces than that observed in dry and wet methods. This phenomenon can be related to less effect of thermo-mechanical stresses on the work part under MQL mode than that can be found in wet mode.

5. References

[1] Wang, Q. and Cáceres, C. H. 1996. Mg Effects on the Eutectic Structure and Tensile Properties of Al-Si-Mg Alloys. Materials Science Forum. 5: 159-164.

[2] Moustafa, M., Samuel, F. and Doty, H. 2003. Effect of Solution Heat Treatment and Additives on the Hardness, Tensile Properties and Fracture Behaviour of Al-Si (A413. 1) Automotive Alloys. Journal of Materials Science. 38: 4523-4534.

[3] Zedan, Y. and Alkahtani, S. 2013. Influence of the Microstructure on the Machinability of Heat-Treated Al–10.8% Si Cast Alloys: Role of Copper-Rich Intermetallics. 2013. Journal of Materials Processing Technology. 213: 167-179.

[4] Sjölander, E. and Seifeddine, S. 2010. The Heat Treatment of Al–Si–Cu–Mg Casting Alloys. Journal of Materials Processing Technology. 210: 1249-1259.

[5] Shivkumar, S., Ricci, S., Steenhoff, B., Apelian, D. and Sigworth, G. 1989. An Experimental Study to Optimize the Heat Treatment of A356 Alloy. AFS Transactions. 97: 791-810.

[6] Hetke, A. and Gundlach, R. 1994. Aluminum Casting Quality in Alloy 356 Engine Components. American Foundrymen's Society. Transactions of the American Foundrymen's Society. 102: 367-380.

[7] Guru, P., Panigrahi, S. and Ram, G. J. 2015. Enhancing Strength, Ductility and Machinability of a Al–Si Cast Alloy by Friction Stir Processing. Journal of Manufacturing Processes. 18: 67-74.

[8] Kilickap, E. 2016. Effect of Cutting Environment and Heat Treatment on the Surface Roughness of Drilled Al/SiC MMC. Materials Testing. 58: 357-361.

[9] Callister, W. D. and Rethwisch, D. G. 2007. Materials Science and Engineering: An Introduction. Wiley New York. 7.

[10] Jorstad, J. L. 1979. Machinability of 380 Alloy: Effect of Minor Elements and Impurities. Transactions of the Society of Die Casting Engineers. 79: 1155-1167.

[11] Jorstad, J. L. 1980. Influence of Aluminum Casting Alloy Metallurgical Factors on Machinability. SAE Technical Paper. 89(2): 1892-1906.

[12] Burant, R. and Skingle, T. 1980. Machining the Silicon-Containing Aluminum Alloys. SAE Technical Paper.

[13] Kelly, J. and Cotterell, M. 2002. Minimal Lubrication Machining of Aluminium Alloys. Journal of Materials Processing Technology. 120: 327-334.

[14] Braga, D. U., Diniz, A. E., Miranda, G. W. and Coppini, N. L. 2002. Using a Minimum Quantity of Lubricant (MQL) and a Diamond Coated Tool in the Drilling of Aluminum–Silicon Slloys. Journal of Materials Processing Technology. 122: 127-138.

[15] Klocke, F. and Eisenblätter, G. 1997. Dry cutting. CIRP Annals-Manufacturing Technology. 46: 519-526.

[16] Davim, J., Sreejith, P., Gomes, R. and Peixoto, C. 2006. Experimental Studies on Drilling of Aluminium (AA1050) under Dry, Minimum Quantity of Lubricant, and Flood-Lubricated Conditions. Proceedings of the Institution of Mechanical Engineers. Part B: Journal of Engineering Manufacture. 220: 1605-1611.

[17] Zedan, Y., Niknam, S. , Djebara, A. and Songmene, V. 2012. Burr Size Minimization When Drilling 6061-T6 Aluminum Alloy. in ASME 2012 International Mechanical Engineering Congress and Exposition. 1053-1059.

[18] Ekici, E. and Motorcu, A. R. 2014. Evaluation of Drilling Al/SiC Composites with Cryogenically Treated HSS Drills. The International Journal of Advanced Manufacturing Technology. 74: 1495-1505.

[19] Sreejith, P. and Ngoi, B. 2000. Dry Machining: Machining of the Future. Journal of Materials Processing Technology. 101: 287-291.

[20] Sekar, K., Kanjirathikal, A. and Joseph, M. 2014. Effect of T6 Heat Treatment in Tribological Properties of A356 Aluminum Alloy Reinforced with Al2O3 Nanoparticles by Combination Effect of Stir and Squeeze Casting Method. in Applied Mechanics and Materials. 968-971.

[21] Shivkumar, S., Keller, C. and Apelian, D. 1990. Aging Behavior in Cast Al-Si-Mg Alloys. AFS Transactions. 98: 905-911.

[22] Tash, M. 2006. Effect of Metallurgical Parameters on the Machining Behaviour of 356 and 319 Alloys. Ph. D. Dissertation. University of Quebec at Chicoutimi.