academicJournals

Vol. 10(2), pp. 71-78, 30 January, 2015
DOI: 10.5897/SRE2014.5929
Article Number:2A15B5A49797
ISSN 1992-2248
Copyright©2015
Author(s) retain the copyright of this article
http://www.academicjournals.org/SRE

Scientific Research and Essays

Full Length Research Paper

Effect of the aging process on mechanical properties and machinability in AA6013 aluminum alloys

Birol Akyüz* and Safa Şenaysoy

Department of Mechanical and Manufacturing Engineering, Bilecik Seyh Edebali University, 11200 Bilecik, Turkey.

Received 14 April, 2014; Accepted 25 November, 2014

This study investigated the effects of aging process on the mechanical properties and machinability in AA6013 aluminum alloy. To this end, AA6013 aluminum alloy samples were maintained in heat treatment furnace at 530°C (for 8 h) and placed in hot water (at 70°C), and then subjected to aging process by storing in heat treatment furnace (at 180°C) for various times (1, 3, 6, 9, 12 and 24 h). Changes in mechanical and machinability properties of samples that underwent aging process were investigated. At the end of the aging process, an increase was observed in mechanical properties of AA6013 alloy. Cutting forces increased during the machining of alloy depending on the increase in aging time. High mechanical properties were obtained at the end of the 6-h aging process of AA6013 aluminum alloy. A significant increase was observed between mechanical properties obtained at the end of the 6-h aging time and machinability properties with values obtained at the end of the 24th hour.

Key words: Machining, aging, AA6013 aluminum alloys, mechanical properties.

INTRODUCTION

The fact that aluminum alloys have such characteristics as being able to develop low density, high specific resistance, high corrosion resistance and mechanical properties, ease of forming and machining enabled creation of areas of use in various sectors. Of these sectors, automotive, transportation, aviation-aeronautics, electronics, machinery, and manufacturing are the leading ones. They are especially important for achieving fuel savings by reducing weight due to being lightweight and in the prevention of air pollution (Florea et al., 2012; Chen et al., 2012; Bakavos and Prangnell, 2010; Siddiqu et al., 2000; Hayat, 2012).

Another important characteristic of aluminum alloys is that the mechanical properties are open to improvement. Depending on the improvement of the mechanical properties of these alloys, numerous areas of use appear. Aging process is quite important in the improvement of mechanical properties of aluminum alloys. Aluminum alloys are named after the alloy elements they contain. One of the aluminum alloys with most widespread areas of use is 6xxx (containing Aluminum-Al, Magnesium-Mg, and Silicon-Si).

As a result of our literature review, some the studies conducted on 6xxx aluminum alloys are as follows.

In a study by Öztürk et al. (2010), AA6061 aluminum alloys were reported to reach maximum hardness value

*Corresponding author. E-mail: birol.akyuz@bilecik.edu.tr, birolakyuz@gmail.com Tel: +90 228 214 15 42. Fax: +90 228 214 12 22.
Author(s) agree that this article remain permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

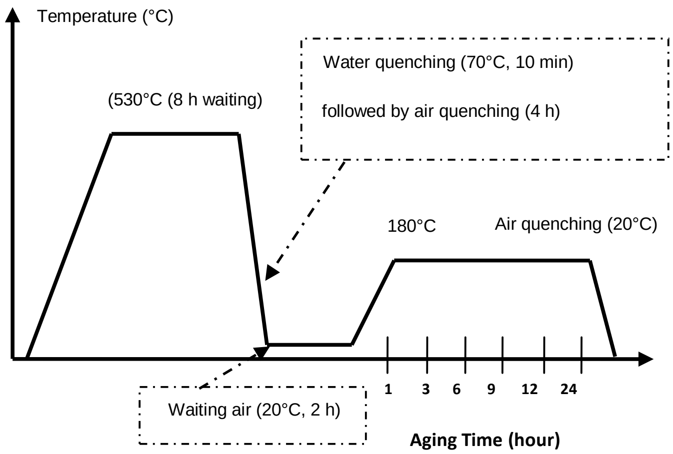

Figure 1. Schematic representation of the aging treatment procedure.

at the end of aging process at 200°C (for 600 min). In a study conducted by Graznya Mrowka-Nowotnik et al. (2005), changes in mechanical properties of AA6005 and AA6082 alloys were investigated under different cooling conditions. They reported that the highest hardness was obtained by cooling in oil. In a study by Meyveci et al. (2010), aging process applied on AA6063 alloy was reported to improve mechanical properties and wear resistance. In their study, Barbosa et al. (2006) investigated mechanical and welding properties of aged 6013 and 6061 alloys. No decrease was reported in mechanical properties following the welding process in 6013 alloy and that the welding property was better. Braun (2006) applied aging process (between 3-100 h, up to 191°C) and investigated tensile, corrosion, and thermal properties of AA6013 alloy. Corrosion resistance of the alloy was reported to increase at the end of aging process. Petroyiannis et al. (2004) examined the effect of corrosion on mechanical properties in 6013 alloy. They reported a reduction in mechanical properties of alloys exposed to corrosion. In a study by Tesch et al. (2007), crack formation of 6013 alloy was investigated by performing fatigue and notch impact tests. Studies reported formation of Mg_2Si intermetallic phases in the microstructure in aging processes of aluminum alloys due to the effect of Mg and Si in alloys. It was suggested that corrosion resistance and strength of alloy increased thanks to the formation of these phases (Zander, 2010; Khalid et al., 2010). In a study by Demir and Gündüz (2009), the effect of aging process on the machinability of AA6061 aluminum alloy was investigated. Cutting forces of aged samples were reported as higher at lower cutting speeds.

Machinability, as a concept, demonstrates the ease or difficulty of the machining of a material in the desired shape, size, and surface quality (Stephenson and Agapiou, 2006; Boothroyd and Knight, 2006). Of the leading properties affecting the machinability of a material, mechanical properties and machining parameters take the lead. They have impact on the cutting forces, surface roughness values, and chip formation occurring during the machining of the material (Kalpakjian and Schmid, 2010; Grover, 2010; Black and Kohser, 2008; Grzesik, 2008).

There is limited number of studies in the literature that investigate the effect of aging process on machinability in AA6013 series aluminum alloys. This study investigated the effects of aging process on the mechanical properties and machinability in AA603 aluminum alloy. Within this scope, changes in mechanical properties of samples that underwent aging process at varying times, their machinability properties, and the correlation between them were investigated.

EXPERIMENTAL PROCEDURE

Mechanical properties

In the experimental study, aging process was applied on AA6013 aluminum alloy samples at varying times. To this end, AA6013 aluminum alloy samples were maintained in heat treatment furnace at 530°C (for 8 h) and placed in hot water (at 70°C), and then subjected to aging process by storing in heat treatment furnace (at 180°C) for different times (1, 3, 6, 9, 12 and 24 h). Aging process was carried out in heat- and time-controlled heat treatment furnace (Protherm 1200°C). Samples were placed in specially designed shelves inside the heat treatment furnace. Samples used in the experiment underwent aging process at times and temperatures noted in Figure 1. Mechanical tests and machinability tests of these samples that underwent aging process were performed. Aging procedures implemented in the experiment are given in Figure 1 and chemical composition of the alloy used is shown in Table 1. AA6013 aluminum alloy samples used in the experiment (24 mm in diameter and 6 m in length) were supplied by Tuncel Metal AŞ.

Hardness tests were conducted in the experimental study. Surfaces of samples used in hardness tests were cleaned by grinding (ranging from 200 up to 1200 grit) (after turning in 15 mm diameter and 12 mm thickness). Hardness test data were obtained by conducting surface measurements (by averaging 10 measurements). Hardness tests were carried out by a Vickers Hardness (HV_{10}) (Shimadzu HMV-2) testing device. Hardness values were established by averaging data (by conducting at least 10 measurements).

In the experimental study, such mechanical tests as Ultimate Tensile Strength (UTS), Yield Strength (YS) and Elongation % (EL%) of samples that underwent aging process were carried out. Samples used in mechanical tests were prepared as per ASTM-E8 standard (10 samples each). By averaging the data obtained from these samples (10 samples from each different aging time), test data were obtained on ultimate tensile and yield strengths and elongation. These tests were conducted at room temperature (20ºC) at 2.5 mm min^{-1} crosshead speed (Shimadzu Autograph AGS-J 10 kN Universal Tester).

Machining properties

In this study, data were obtained on cutting forces by keeping the

Table 1. Chemical composition of the studied AA6013 aluminum alloy (*Wt %).*

Parameter	Fe	Si	Cu	Mn	Mg	Zn	Ti	Cr	Al
AA6013	0.5	1.0	0.8	0.5	0.9	0.1	0.1	0.1	Rest

Table 2. Machining parameters and conditions used during the test.

Parameter	Depth of cut DoC (mm)	Cutting speed V_c (m/min)	Aging temperature (°C)	Aging time (h)
AA6013	0.10, 0.25, 0.50	60, 120, 180	180°C	1, 3, 6, 9, 12, 24

chip section fixed at varying cutting speeds on AA6013 aluminum alloy samples that underwent aging process at varying times. During the application, the machinability of alloys were investigated by examining the changes in cutting forces (at varying cutting speeds and varying depths of cut) depending on the aging time.

A DMG Alpha 300 CNC turning lathe was used in machinability experiments. Data were obtained under dry machining conditions and vertical processing method. A Polycrystalline Diamond (PCD) (CCGT 120408 FL K10) was used as the cutting edge in the experiments. Surface roughness values of samples (Ra-µm) were measured by a surface roughness measuring device (TIME TR200). Data on cutting forces were obtained from a specially designed strain gauge (Figure 2).

After the cleaning chip was removed from the surfaces of samples used in the experiment (20 mm in diameter), data on cutting forces were obtained. Data on cutting forces obtained from the experiment were classified according to aging times, and graphs were prepared. Machining parameters used in the experimental study are given in Table 2.

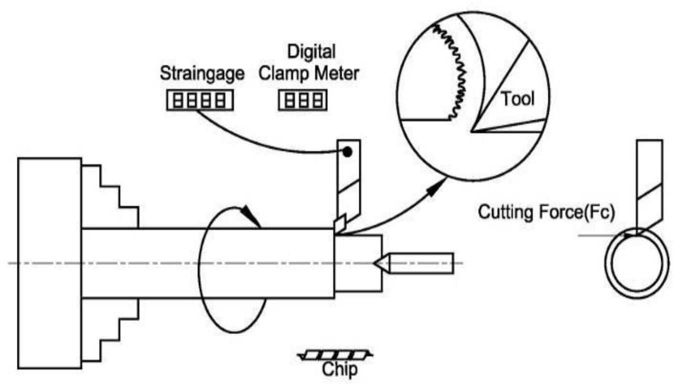

Figure 2. Schematic representation of experimental set-up with strain gauge.

EXPERIMENTAL RESULTS AND DISCUSSION

Mechanical properties

Hardness values obtained as a result of aging process of AA6013 aluminum alloy are given in Figure 3. Depending on the aging time, an increase was observed in hardness values of AA6013 alloy. As can be seen in Figure 3, mean hardness values were measured in unaged reference sample as 51.5 HV_{10}, in samples aged for 6 h as 130.2 HV_{10}, in samples aged for 12 h as 132.4 HV_{10}, and in samples aged for 24 h as 138.1HV_{10}. Hardness of the unaged sample demonstrated a vast increase at the end of 6-h aging (over 2.5 times). A major difference was not observed between the hardness values obtained at the end of 6-h and 24-h aging times (~5%). As a result of the study, it was observed that the hardness value of alloy increased parallel to the aging time. The hardness increase in alloy as a result of aging process may be explained by phases formed within the microstructure, precipitation, and change in grain sizes.

Figure 3. Hardness values obtained at various aging times of AA6013 alloy.

Data on ultimate tensile strengths (UTS), Yield Strengths (YS) and Elongation % (EL%) amount of AA6013 aluminum samples that underwent aging process in the study are given in Figure 4 and 5. When

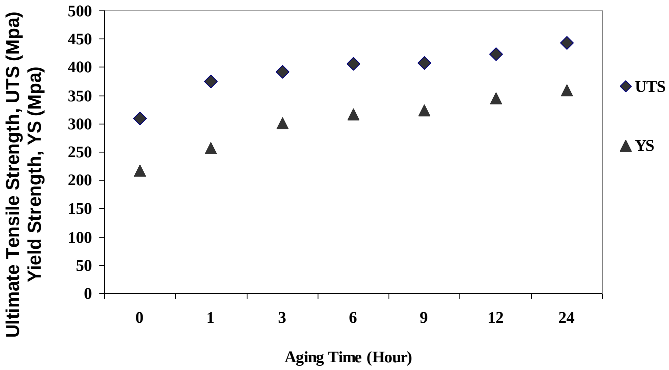

Figure 4. Tensile and yield strength values obtained from various aging times in AA6013 alloy.

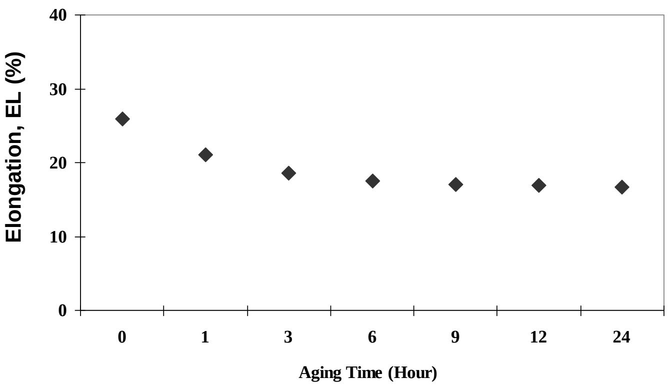

Figure 5. Elongation % values obtained from various aging times of AA6013 alloy.

examined the UTS and YS values of samples in Figure 4, the obtained values were 309.3 MPa UTS and 216.9 MPa YS in unaged reference sample, 410.6 UTS and 316.9 YS in the samples aged for 6 h, 422.7 UTS and 340.8 YS in samples aged for 12 h, and 442.4UTS and 352.5YS in samples aged for 24 h. While a major increase was observed in UTS and YS values of unaged sample at the end of 6-h aging (~32%), a significant increase was not found after 6 h. A significant difference was not observed in the experiment between UTS and YS values obtained at the end of 6-h and 24-h aging (~7%). When examined Figure 5, while the highest EL% value obtained in the experiment was from the unaged reference sample (25.9%), it was 17.4% for the sample aged for 6 h, 16.9% for the sample aged for 12 h, and 16.5% for the sample aged for 24 h. It was observed from the experimental study that UTS and YS values of the alloy increased due to the rise in aging time in AA6013 alloy subjected to the aging process while the elongation % value saw a decrease. These results are in accordance with the literature.

Machining properties

Data on cutting forces obtained from the machining of AA6013 aluminum alloy that was implemented aging process in the experimental study are given in Figure 6a to c. When examined Figure 6a to c, an increase was observed in the cutting forces of the alloy depending on the rise of aging time. Similarly, cutting forces increased depending on the depth of cut.

When analyzed the cutting forces formed depending on the aging times of alloy in Figure 6a, it was measured at 60 m.min^{-1} cutting force (DoC:0.5mm) as 30.7 N in unaged reference sample, 51.9 N in the sample aged for 6 h, 52.4 N in the sample aged for 12 h, and 53.8N in the sample aged for 24 h. In Figure 6a, it was measured at 180 m.min^{-1} cutting force (DoC:0.5 mm) as 21.4 N in unaged reference sample, 43.6 N in the sample aged for 6 h, 44.1 N in the sample aged for 12 h, and 45.7 N in the sample aged for 24 h. When compared the cutting forces obtained from the unaged reference sample and cutting forces measured from samples that were implemented a 6-h aging process, an increase over 70% was observed in cutting forces at the end of 6 h (Figure 6a). On the other hand, when compared the cutting forces obtained from the sample that was aged for 6 h and the sample aged for 24 h, a significant difference was not observed (max.0.2%) between them. From this point of view, it may be noted that the highest cutting force was reached in samples that were implemented a 6-h aging process.

When Figure 6a to c was analyzed, it was observed that cutting forces decreased along with the rise in cutting speed in all samples that underwent aging process (Figure 6a to c). While the highest cutting force in all samples that were implemented aging process (at all depths of cut) occurred at 60 m.min^{-1} cutting speed, the lowest cutting force was obtained at 180 m.min^{-1} cutting speed. Cutting forces increased along with rises in depths of cut in all samples that underwent aging process (Figure 6a to c). The highest cutting force at all depths of cut and at all cutting speeds was reached in samples aged for 6 h. From this viewpoint, when compared the machinability of unaged reference sample and samples aged for 6 h, the machinability of samples aged for 6 h became difficult (above ~70%). However, a significant difference was not observed between the machinability of samples aged for 6 h and samples aged for 24 h (~0.2%).

In the experimental study, it was observed in AA6013 aluminum alloy that the cutting forces occurred at 60 *m.min^{-1}* cutting speed were higher compared to cutting forces obtained at a cutting speed of 180 *m.min^{-1}* (Figure 6a to c). In the light of this, the reason for higher cutting

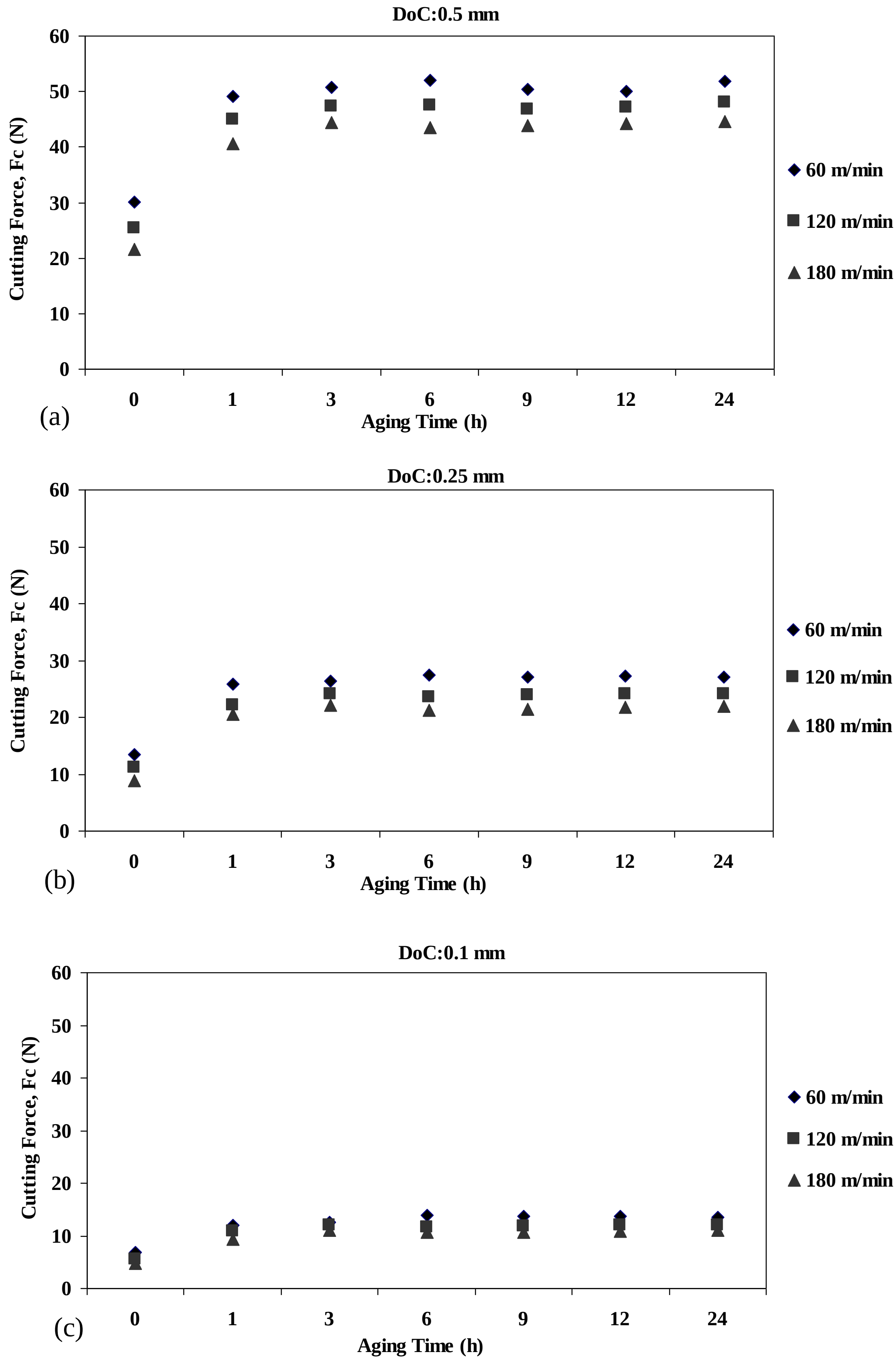

Figure 6. Cutting speeds obtained at different aging times in AA6013 alloy (F_C) (DoC: (a) 0.5 mm (b) 0.25 mm and (c) 0.1 mm respectively.

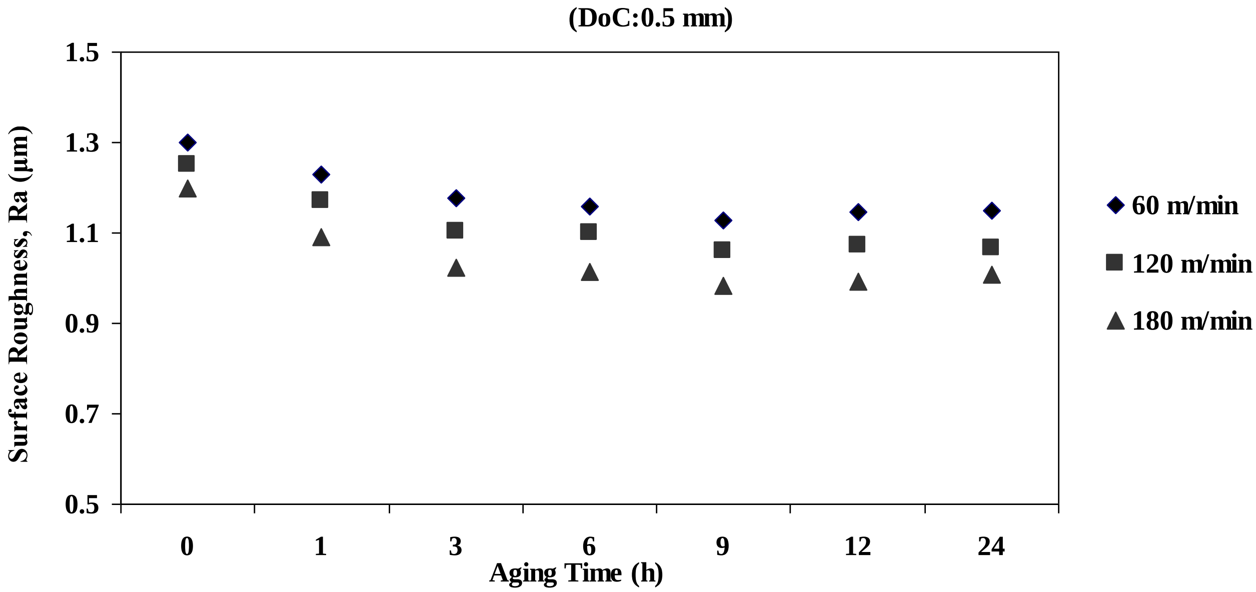

Figure 7. Surface roughness values obtained from various aging times of AA6013 alloy (R_a) (DoC:0.5 mm).

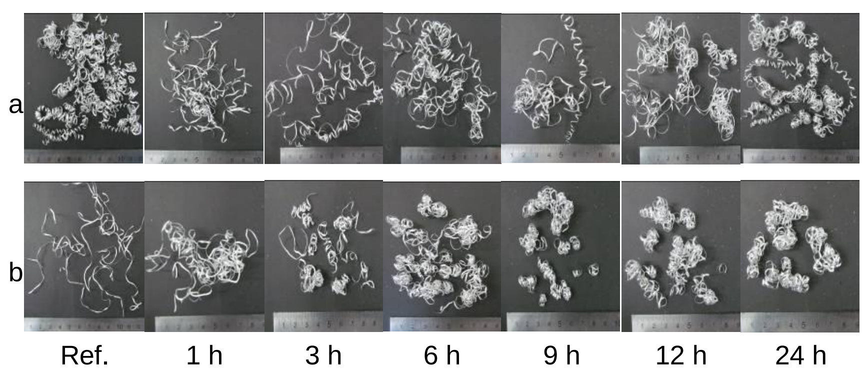

Figure 8. Chip images formed at varying aging times in AA6013 alloy and at a) 60 $m.min^{-1}$ and b) 180 $m.min^{-1}$ cutting speed (DoC:0.5 mm).

forces at lower cutting speeds in AA6013 alloy is due to work hardening depending on dislocation deposit at the time of cutting. The fact that the movement of dislocations is difficult against plastic deformation at lower cutting speeds (lower revolutions) causes an increase in cutting forces.

Surface roughness values measured on experimental samples machined in the experiment (at 0.5 mm depth of cut) are given in Figure 7. It was observed that surface roughness values dropped along with the increase in cutting speed while machining the samples at all aging times. Therefore, the highest surface roughness value at all aging times appeared at 60 $m.min^{-1}$ cutting speed. An increase was observed in cutting forces as a result of chips depositing on the cutting surface at lower cutting speeds. It may be noted that, since deposit chip was formed, this caused surface roughness values to increase (Stephenson and Agapiou, 2006; Boothroyd and Knight, 2006; Kalpakjian and Schmid, 2010; Grover, 2010).

Chip images obtained from the machining of AA6013 alloy subjected to aging process are given in Figure 8. Analysis of chip images reveals a shortening in chip lengths depending on the increase in aging time. Similarly, a shortening occurred in chip lengths depending on the increase in cutting speed. A continuous chip formation occurs along with deposit chip formation at lower cutting speeds and chips are formed by ductile fracture, and elongation occurs in chip lengths. Surface roughness values increased thanks to this deposit chip. Longer chips at lower cutting speeds might be interpreted as the occurrence of ductile fractures (Kalpakjian and Schmid, 2010; Grover, 2010; Black and Kohser, 2008; Grzesik, 2008). Shortening of chip lengths thanks to an increase in cutting speed may be explained by the formation of a more brittle structure as a result of a rise in the hardness of alloy (Figure 8). A gradual shortening is observed in chip lengths due to the formation of a more brittle structure. From this point of view, AA6013 alloy that was implemented an aging process may be noted to become gradually brittle depending on the increase in aging time of samples (Figure 8). Data obtained in this section are in accordance with the data from mechanical tests in the experimental study (Figures 3 to 5.).

Depending on the aging time, an increase was observed in mechanical properties of the alloy. This increase in the mechanical properties had an impact on the machinability properties of alloys. Due to the differences in fine precipitations formed in the alloy depending on the aging process, hardness and strength results were also believed to be different. Since fine precipitations formed within grain in alloy following aging process hampered or prevented the movement of dislocations during deformation, an increase was observed in mechanical properties (hardness, yield and tensile strengths). From this point of view, the reason for higher cutting forces at lower cutting speeds in AA6013 alloy stems from work hardening due to dislocation deposit during cutting. The fact that dislocation movement being difficult against plastic deformation at lower cutting speeds (lower revolutions) causes an increase in cutting forces (Stephenson and Agapiou, 2006; Grzesik, 2008).

Conclusions

This experimental study investigated the effects of aging process on the mechanical properties and machinability in AA603 aluminum alloy. Results obtained from the experimental study are as follows:

1) At the end of the aging process, such mechanical properties as hardness (HV), UTS, and YS of AA6013 alloy increased due to aging time. However, elongation % value (EL%) decreased depending on the increase in aging time. The alloy reached higher mechanical properties at the end of 6-h aging time. A significant difference was not observed between UTS and YS values obtained at the end of 6-h aging and 24-h aging (~7%). Similarly, in hardness value, a significant difference was not established between the hardness values obtained at the end of 6-h and 24-h aging times (~5%).

2) A decrease was observed in cutting forces as the cutting speed rose. The highest cutting forces occurred at the lowest cutting speed. The reason for high cutting forces at lower cutting speeds (lower rotations per minute) is due to work hardening depending on dislocation deposit at the time of cutting. Therefore, cutting forces occurred at 60 $m.min^{-1}$ cutting speed were higher compared to those occurred at 180 $m.min^{-1}$ cutting speed.

3) Since cutting forces increased depending on the rise in aging time, machinability of the alloy demonstrated a decrease depending on the aging time.

4) Cutting forces increased as the depth of cut rose. The highest cutting forces occurred in 0.5 mm depth of cut and at 60 $m.min^{-1}$ cutting speed. Surface roughness values improved depending on the aging time and cutting speed increases.

Conflict of Interest

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENT

A heat treatment furnace that was purchased within the scope of a project conducted by the author (Bilecik S.E. University, BAP: 2012–01 BİL.03-02) was used in this study.

REFERENCES

Bakavos D, Prangnell PB (2010) Mechanisms of joint and microstructure formation in high power ultrasonic spot welding 6111 aluminium automotive sheet. Mater. Sci. Eng. A 527:6320–6334.
Barbosa C, Dille J, Delplancke JL, Rebello JMA, Acselrad O (2006). A microstructural study of flash welded and aged 6061 and 6013 aluminum alloys, Mater. Characteriz. 57:187-192.
Black JT, Kohser RA (2008). Materials and Processes in Manufacturing (10th Ed.), John Wiley & Sons, Inc.
Boothroyd G, Knight WA (2006). Fundamentals of Machining and Machine Tools, (3rd Ed.), Taylor & Francis.
Braun R (2006). Investigations on the long-term stability of 6013-T6 sheet. Mater. Characteriz. 56:85–95.
Chen YC, Bakavos D, Gholinia A, Prangnell PB (2012). HAZ development and accelerated post-weld natural ageing in ultrasonic spot welding aluminium 6111-T4 automotive sheet. Acta Materialia 60:2816–2828.
Demir H, Gündüz S (2009). The effects of aging on machinability of 6061 aluminium alloy. Mater. Des. 30:1480–1483.
Florea RS, Solanki KN, Bammann DJ, Baird JC, Jordon JB, Castanier MP (2012). Resistance spot welding of 6061-T6 aluminum: Failure loads and deformation. Mater. Des. 34:624–630.
Grover MP (2010). Principles of Modern Manufacturing (4th Ed.), John Wiley & Sons, Inc.
Grzesik W (2008). Advanced Machining Processes of Metallic Materials, Elsevier, UK.
Hayat F (2012). Effect of aging treatment on the microstructure and mechanical properties of the similar and dissimilar 6061-T6/7075-T651 RSW joints, Mater. Sci. Eng. A 556:834-843.

Kalpakjian S, Schmid SR (2010). Manufacturing Engineering and Technology, Prentice Hall.

Khalid RH, Ram GDJ, Phanikumar G, Rao KP (2010). Microstructure and tensile properties of friction welded aluminum alloy AA7075-T6. Mater. Des. 31:2375-2380.

Meyveci A, Karacan İ, Çalıgülü U, Durmuş H (2010). Pin-on-disc characterization of 2xxx and 6xxx aluminium alloys aged by precipitation age hardening. J. Alloys Compounds 491:278–283.

Mrowka-Nowotnik G, Sieniawski J (2005). Influence of heat treatment on the microstructure and mechanical properties of 6005 and 6082 aluminium alloys. J. Mater. Process. Technol. 162–163:367–372.

Öztürk F, Sisman A, Toros S, Kilic S, Picu RC (2010) Influence of aging treatment on mechanical properties of 6061 aluminum alloy. Mater. Des. 31:972–975.

Petroyiannis PV, Kermanidis AT, Papanikos P, Pantelakis SG (2004). Corrosion-induced hydrogen embrittlement of 2024 and 6013 aluminum alloys. Theor. Appl. Fracture Mech. 41:173–183.

Siddiqu RA, Abdullah HA, Al-Belushi KR (2000). Influence of aging parameters on the mechanical properties of 6063 aluminium alloy. J. Mater. Process. Technol. 102:234-240.

Stephenson DA, Agapiou JS (2006). Metal Cutting Theory and Practice (2.nd Ed.), Taylor & Francis.

Tesch A, Pippan R, Trautmann KH, Döker H (2007). Short cracks initiated in Al 6013-T6 with the focused ion beam (FIB)-technology. Int. J. Fatigue 29:1803-1811.

Zander J, Sandström R (2008). One parameter model for strength properties of hardenable aluminium alloys. Mater. Des. 29:1540–1548.