

Analysis of artificial aging with induction and energy costs of 6082 Al and 7075 Al materials

Mehmet Taştan^a, Hayrettin Gökozan^a, Pınar Sarı Çavdar^b, Gürkan Soy^c, Uğur Çavdar^{d,✉}

^aCelal Bayar University, Turgutlu Vocational School, Department of Electric & Energy, 45400 Manisa, Turkey

^bIzmir Demokrasi University, Engineering Faculty, Civil Engineering Department, IDU Campus, 35140, Izmir, Turkey

^cCelal Bayar University, Turgutlu Vocational School, Department of Machinery, 45400 Manisa, Turkey

^dIzmir Demokrasi University, Engineering Faculty, Mechanical Engineering Department, IDU Campus, 35140, Izmir, Turkey

✉Corresponding author: ugur.cavdar@idu.edu.tr

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ABSTRACT: In the study, 6082 Al and 7075 Al samples were subjected to a solution taking place at 580 °C for 1 min using ultrahigh frequency induction heating system (UHFIHS) and water was supplied at the end of the process. Artificially aging was then carried out at 190 °C for 2, 4, 6 and 8 min. In both applications, heating was carried out using an induction system with a frequency of 900 kHz and a power of 2.8 kW. For these aluminum series and shapes, induction heating and heat treatment costs in different shapes are calculated. In addition, the hardness values obtained from artificially aged 6082 Al and 7075 Al samples at 190 °C for 10 h were compared with conventional methods after 5 h at 540 °C for 5 h. As a result, the hardness values of 6082 Al samples, which were obtained in 10 h by conventional methods, were obtained by artificial aging for only 8 min using induction system.

KEYWORDS: 6082 Al; 7075 Al; Energy cost; Energy consumption; UHFIHS

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RESUMEN: *Análisis del envejecimiento artificial en horno de inducción y los costos de energía de los materiales 6082 Al y 7075 Al.* Muestras de las aleaciones 6082 Al y 7075 Al se sometieron a un tratamiento térmico en horno de inducción de ultraalta frecuencia (UHFIHS) a 580 °C durante 1 min y suministro de agua al final del proceso. El envejecimiento artificial se llevó a cabo a 190 °C durante 2, 4, 6 y 8 min. En ambas aplicaciones, el calentamiento se llevó a cabo utilizando un sistema de inducción con una frecuencia de 900 kHz y una potencia de 2,8 kW. Para estas series y diseños de aluminio, se calcularon los costos del tratamiento térmico. Adicionalmente, se compararon los valores de dureza de las muestras de 6082 Al y 7075 Al envejecidas artificialmente a 190 °C durante 10 h con los métodos convencionales 540 °C durante 5 h. Los resultados de dureza de la muestra 6082 Al obtenidos en 10 h mediante métodos convencionales, tardaron sólo 8 min mediante el envejecimiento artificial con el sistema de inducción.

PALABRAS CLAVE: 6082 Al; 7075 Al; Consumo de energía; Costo energético; UHFIHS

ORCID ID: Mehmet Taştan (<https://orcid.org/0000-0003-3712-9433>); Hayrettin Gökozan (<https://orcid.org/0000-0002-8917-4001>); Pınar Sarı Çavdar (<https://orcid.org/0000-0002-1989-4759>); Gürkan Soy (<https://orcid.org/0000-0002-0308-1702>); Uğur Çavdar (<https://orcid.org/0000-0002-3434-6670>)

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1. INTRODUCTION

Aluminum and alloys are widely used in machinery, electronics, automotive and aerospace industries due to their high mechanical properties and high machinability as well as high electrical conductivity, high corrosion resistance, low density and fatigue resistance (Güleryüz and Kaçar, 2011; Güven and Delikanlı, 2012; Yılmaz *et al.*, 2012;; Akyüz and Şenaysoy, 2014).

In particular, its weight is three times lower than the standard, it has an important place in the aviation and automotive sector to save fuel and reduce emissions. Among the most important advantages of aluminum and its alloys is that the mechanical properties can be improved by different heat treatments applied according to the desired properties (Güleryüz and Kaçar, 2011; Güven and Delikanlı, 2012; Akyüz and Şenaysoy, 2014).

6000 Series aluminum alloys contain magnesium (Mg) and silicon (Si) elements, have high strength and corrosion resistance, they can be strengthened by precipitation hardening. This, in turn, provides advantages in terms of ease of handling, welding and shaping. They are primarily used in the automotive industry and in the manufacture of extruded products (Şişmanoğlu, 2009).

7000 Series aluminum alloys contain zinc (Zn) element. It is the alloy with the highest hardness and strength value in the aluminum alloys thanks to the precipitation hardening. It is used especially in the aerospace sector where aircraft parts are manufactured and high strength is required (Şişmanoğlu, 2009).

The precipitation hardening process is applied to aluminum alloys in order to increase their strength and hardness (Güven and Delikanlı, 2012; Dilmeç *et al.*, 2015). This process is aimed at making homogeneous and stacked sediments in grain boundaries, transforming it into a homogeneous and dense sedimentary structure. This process is carried out in three steps as solution taking, watering and aging. The samples to be precipitated are heated to the receiving temperature to the solution. A homogeneous solid solution is then dissolved by standing at temperature until it is formed. It is then rapidly cooled to obtain an oversaturated solution. Thus, an oversaturated and homogeneous solution is obtained. At the last stage, the sample is subjected to natural or artificial aging in order to create a stable and homogeneous internal structure (Dilmeç *et al.*, 2015).

Akyüz and Şenaysoy (2014) have investigated the effect of aging of AA6013 and AA6082 aluminum alloys on the mechanical and machinability properties of alloys. AA6082 and AA6013 samples were subjected to a solution in 8 h at 530 °C in a heat treatment furnace. The samples were then subjected to artificial aging at 1, 3, 6, 9, 12 and 24 h in a heat

treatment oven heated to 180 °C after being thrown into hot water at 70 °C. After aging, the mechanical properties of AA6013 and AA6082 alloys were observed to increase (Akyüz and Şenaysoy, 2014).

Özdoğan and Kayalı (2011) performed aging heat treatments at different temperatures by applying high plastic deformation to the aluminum alloys of AA 6082 and AA 6082-Zr-Sc with the co-channel angular extrusion (EKAP) technique. They found that the hardness values of the samples were equal in the heat treatment. The structure and hardness values obtained after EKAP at high temperatures of the aluminum alloy containing Zr and Sc are preserved and it is observed that AA 6082 alloy without Zr and Sc recrystallized at low temperatures.

Yılmaz *et al.* (2012) 7075 investigated the remelting and re-aging (RRA) heat treatments of aluminum alloys. T6 aged aluminum alloys were re-dissolved in the temperature range of 180-260 °C for 15-75 min and then resuspended in the samples for 24 h at 120 °C. With this study, they found that the temperature and duration of re-precipitation affected the abrasion resistance and hardness of the sample. They observed that the highest hardness value and wear resistance reached by the alloy resolved at 220 °C temperature and 60 min.

Güleryüz and Kaçar (2011) took AA7075 aluminum alloys in solution at 480 °C for 2 h and then rapidly cooled with water. At the end of this procedure, the samples were briefly subjected to 8% pre-deformation. They then aged at 140 °C for 0.5 to 96 hours at different times in the oven. As a result of the T6 heat treatment, it was observed that tensile strength, yield strength and hardness were increased but deformation was decreased at the percent elongation at the time of deformation aging. As a result, they stated that deformation aging can increase the mechanical properties of AA7075 alloys.

In their study, (Çavdar and Atik, 2014) performed sintering of pure iron and iron based powder metal (PM) fragments with a medium frequency 30 kHz induction using a moving system. With conventional sintering, the average energy consumption of the PM samples was 82 kW/h, and when the induction system was used, the average energy consumption was calculated as 24.49 kW/h. As a result, it has been observed that the medium frequency induction sintering method consumes approximately 3.5 times less electricity per kilogram.

In the study of (Taştan *et al.*, 2015) Ti-6Al-4V samples were subjected to T6 heat treatment with 900 kHz UHFHS. First, Ti samples were dissolved by heating at 900 °C for 60 seconds with induction, and the samples were cooled in water to obtain an oversaturated solid solution. They were then subjected to artificial aging by heating at 600 °C - 900 °C for 30 seconds at 4 different temperatures. The heat treatment costs of Ti samples were found to be between 0.3781 \$/kg and 0.4022 \$/kg.

Gokozan *et al.* (2016) studied the cost analysis of iron and iron-based samples, the cost of sintering, hot pressing and welding using ultra-high frequency induction heating system (UHFIHS) as a heater, and their energy consumption. PM busing and cold-pressed pure iron PM compactors were sintered by induction to calculate the production costs as 0.0619 \$/kg and 0.0688 \$/kg, respectively. It was found that the production cost of induction heating hot pressing under 40 bar pressure was 0.0895 \$/kg. In addition an iron-based bulk and TM specimen Ultra-high frequency welding (UHFIW) was applied with a 5 bar pressure and the total cost was calculated to be 0.1358 \$/kg and 0.0904 \$/kg, respectively.

Induction systems are named according to the frequency type they use. In the literature, systems operating in the frequency range 1-3 kHz and below are called low frequency, systems operating in the frequency range of 3-50 kHz, medium frequency and systems operating in the frequency range of 50-200 kHz are called high frequency. Since an induction system of 900 kHz is not used in previous studies, (Çavdar and Atik, 2014; Çavdar and Gulsahin, 2014; Çavdar and Kusoglu, 2014; Çavdar *et al.*, 2014; Çavdar and Çavdar, 2015; Gezici *et al.*, 2018) in previous work, named this system as ultra-high frequency.

The purpose of this work is to induce T6 heat treatment, which is generally applied to samples 6082 Al and 7075 Al series, as an alternative to conventional methods. 6082 Al, 7075 Al samples were heated to 580 °C by induction and the solution was taken and water was supplied. The aluminum samples were then heated by induction at 190 °C and artificially aged for 2, 4, 6 and 8 min. Cost analysis of induction deposition hardening process for cylindrical, hexagonal and square specimens, which are the most used aluminum block forms in industrial applications. In addition, the values of precipitation hardening applied by induction and hardness values of samples subjected to precipitation hardening by conventional methods were compared.

2. MATERIALS AND METHODS

The contents of 6082 series and 7075 series aluminum parts are given in Table 1. Both types of aluminum specimens were machined on CNC bench, cylinder, hexagonal and square. The dimensions of the parts are given in Fig.1.

TABLE 1. Weight (Wt.%) ratios of 6082 Al and 7075 Al series samples

Al Type	Al	Fe	Si	Cu	Mn	Mg	Zn	Cr	Zi+Ti	Other
6082	Base	0.5	0.7–1.3	0.1	0.4–1.0	0.6–1.2	0.2	0.15	–	0.15
7075	Base	0.5	0.5	1.2–2.0	0.3	2.1–2.9	5.1–6.1	0.18–0.28	0.25	0.15

The pictures of the parts are comparable to the 2 Euro coin in Fig. 2. 6082 series and 7075 series aluminum pieces were subjected to T6 heat treatment using two different methods.

In one method the Al parts were heated with UHFIHS and in the second method using the conventional method with the Chamber furnace. Table 2 shows codes assigned to aluminum samples for 18 different test parameters.

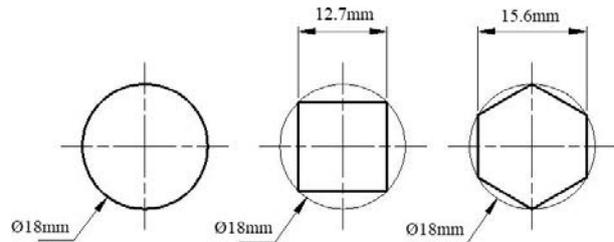


FIGURE 1. Measurements of aluminum parts.



FIGURE 2. Dimensions of aluminum parts compared to 2 Euro.

TABLE 2. Codes assigned to aluminum samples for different experimental parameters

Production Form	Process	Aluminum Type lüminyum Türü	
		6082	7075
Cylinder	Heating to 580 °C	S1	S10
	Heating to 190 °C	S2	S11
	T6 heat treated sample with conventional method.	S3	S12
Hexagonal	Heating to 580 °C	S4	S13
	Heating to 190 °C	S5	S14
	T6 heat treated sample with conventional method.	S6	S15
Square	Heating to 580 °C	S7	S16
	Heating to 190 °C	S8	S17
	T6 heat treated sample with conventional method.	S9	S18

In the first heat treatment method, heating was performed using UHFHS having a frequency of 900 kHz and a power of 2.8 kW. Infrared temperature sensor with $\pm 5\text{ }^\circ\text{C}$ error value is used in the system. Both Al samples were heated to $580\text{ }^\circ\text{C}$ and the solution was removed and then water was added. The Al samples were then heated to $190\text{ }^\circ\text{C}$ and artificially aged for 2, 4, 6 and 8 min. These operations are shown in Fig. 3.

Figure 4: In a, b and c images of the heating processes with the induction system was given. Each sample was placed in the center of the single winding induction coil, and homogeneous heating of the samples was ensured.

In the second heat treatment method, the samples were heated using a Proterm brand Chamber Furnace with a power of 2 kW. 6082 Al and 7075 Al series samples were allowed to stand in the oven at about $540\text{ }^\circ\text{C}$ for 5 h and then water was added. Following this procedure, the samples were artificially aged for 10 h at $190\text{ }^\circ\text{C}$. The total heat treatment time was 15 h. Hardness values were measured with TIME TH-140 Digital Hardness Tester. The hardness of each sample was found by taking the averages of the values obtained from 5 different points. Electrical data such as current, voltage, and power factor for the experimental runs were recorded with the LabVIEW™ 8.5 graphical interface program on a National Instruments data acquisition card in accordance with the relevant IEC standards. Required calculations were made by using the power parameters obtained by the data collection system (Taskin and Gokozan, 2011; Gokozan *et al.*, 2014; Ozdemir and Taştan, 2014).

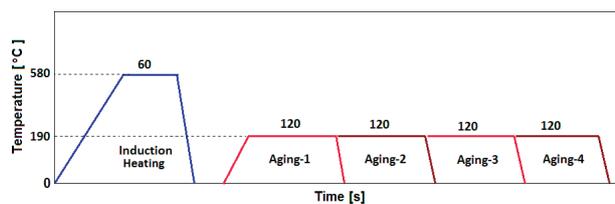


FIGURE 3. Temperature and time chart of solubilization and artificial aging of 6082 Al and 7075 Al samples.

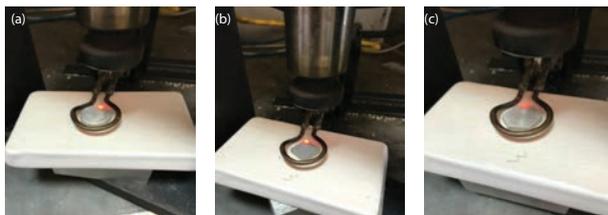


FIGURE 4. Views during heating of Al particles; a) cylinder, b) square, c) hexagon.

3. RESULT AND DISCUSSION

Figure 5 shows the change of the current drawn during the 1st induction process of the 6082 Al cylinder sample with time. The sample set pulled an average of 25 A currents for approximately 12 s until the set reached temperature. After the set temperature has been reached, it continues to operate at a constant current of around 10 A for 60 s.

Figure 6 shows the change of the current drawn during the 2nd operation of the 7075 Al cylinder sample with time. The sample pulled an average of 28 A currents for approximately 6 s until the set reached temperature. After reaching the set temperature, it continued to operate with a constant current of 9 A for 120 s.

Figure 7 shows the change in power of the 7075 Al hexagonal sample over time during induction. The sample consumes an average of 4.5 kW for approximately 8 s until the set reaches temperature. After reaching the set temperature, it continued to operate with constant power around 1.7 kW for 60 s.

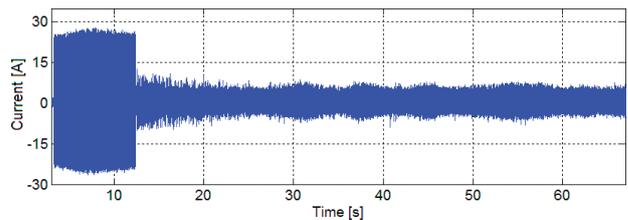


FIGURE 5. Cylinder Part 1 Induction Current Chart.

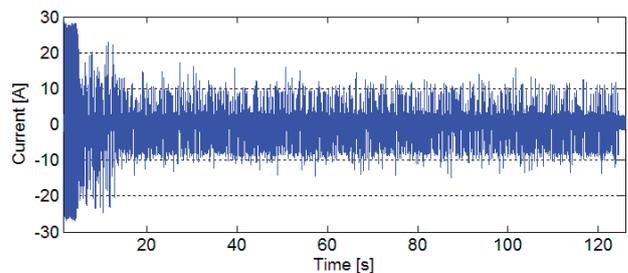


FIGURE 6. 7075 Al Cylinder Part 2 Aging Current Chart.

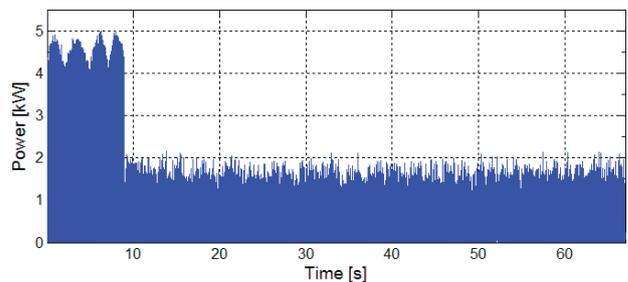


FIGURE 7. 7075 Al Hexagon Part 1 Induction Power Exchange Chart.

Figure 8 shows the time-dependent power changes for induction at 580 °C for 6082 Al. When the graph is examined, it is seen that the sample shapes have an effect on the power consumption and the square sample consumes the most power. The power consumption values in Table 3 also support the situation.

Figure 9 shows the time-dependent power changes of the induction process at 580 °C for the 7075 Al. Here too, the shape difference of the samples affected the power consumption.

The cost analysis of the system on the results of 6082 Al and 7075 Al samples taken at 580 °C temperature by induction and the cost per kilogram of the system with 4 different artificial aging results

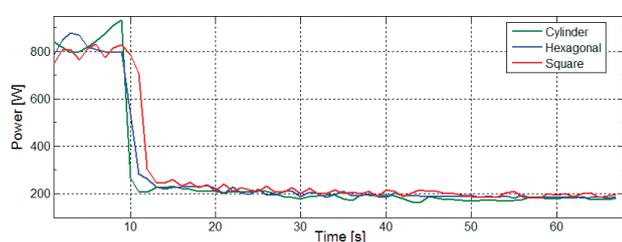


FIGURE 8. Power changes for induction at 580 °C for 6082 Al.

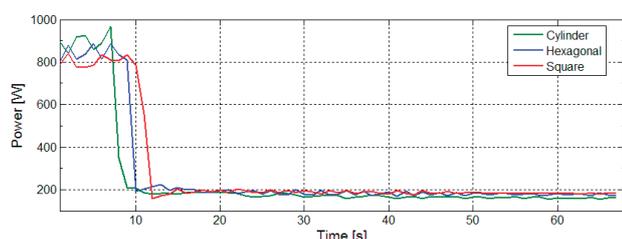


FIGURE 9. Power changes for induction at 580 °C for 7075 Al.

at 2, 4, 6 and 8 min at 190 °C with induction are given in Table 3.

As shown in Fig. 3, experiments were carried out by adding 2 min for each aging step. As the aging time for each sample increases, the production costs increase with this time. When aluminum samples are compared according to their shapes, it is seen that the production costs are lower in roller samples and higher in square samples. When the production costs of 6082 Al and 7075 Al samples are compared among themselves, it is seen that the production costs of 6082 Al sample are higher. 6082 Al, 7075 Al hardness values obtained by induction, hardness values obtained by 4 different artificial aging at induction times of 2-8 min and hardness values obtained by conventional methods are given in Table 4. The error margin obtained for hardness values is $\pm 8\%$.

The presence of cylinders and hexagons of aluminum parts did not affect the hardness values. However, it was determined that square samples of aluminum samples had an increase of roughly 5% in hardness. While the induction coil design is performed, the induction is usually wound in the same way as the part shapes, in order to be more homogeneously influenced by the magnetic field.

Although the induction system used is an induction boom cylinder, it is interesting that the highest hardness values occur in square samples. The hardness values obtained by artificial aging as a result of artificial aging of about 8-12 h were reached in 8 min at 190 °C using the UHFHS system for 6082 Al sample. However, for the 7075 series aluminum sample, artificial aging with induction of 8 minutes was not enough and the hardness value was found to be approximately 19% less. 7075 Al sample did not exhibit a significant increase as a result of the

TABLE 3. The cost of aluminum sampling with the induction system for solubilization and aging

Aluminum Type	Production Form	580 °C Induction (\$/kg)	1. Aging (\$/kg)	2. Aging (\$/kg)	3. Aging (\$/kg)	4. Aging (\$/kg)
6082	Cylinder	0.1898	0.3467	0.5212	0.6783	0.8352
	Hexagonal	0.2257	0.4084	0.5915	0.7698	0.9481
	Square	0.2906	0.5230	0.7446	0.9627	1.1808
7075	Cylinder	0.1653	0.3125	0.4652	0.6241	0.7713
	Hexagonal	0.2046	0.3658	0.5326	0.7047	0.8659
	Square	0.2682	0.4838	0.6899	0.9028	1.1089

TABLE 4. HB hardness values of aluminum samples

Aluminum Type	Precipitation hardening is the resultant hardness value (HB)	Artificial aging results with induction hardness value (HB)				The artificial aging resultant hardness value by conventional method (HB)
		1. Aging (2 min)	2. Aging (4 min)	3. Aging (6 min)	4. Aging (8 min)	
6082	50	66	88	92	95	95
7075	72	106	112	118	122	150

application of artificial aging at 10 and 12 minutes with induction. 6082 Al and 7075 Al samples were stored for 5 hours at a temperature of 540 °C for a 2 kW Chamber furnace used in conventional heating, resulting in a power consumption of 5.36 kW and a power consumption of 0.5249 \$/kg. Following this operation, a 1.95 kW power and 0.1909 \$ / kg energy cost were calculated for the samples at 190 °C for 10 hours of artificial aging. The total heat treatment duration lasted 15 hours, with a total power of 7.31 kW and an energy cost of 0.7158 \$/kg.

Çavdar and Atik (2014) found that the medium-frequency induction sintering method they used consumed about 3.5 times less electricity per kilogram. In this study, when compared with the induction heating method by the conventional method, it is seen that the induction heating consumes approximately 2.3 times less electricity energy.

In the study of (Taştan *et al.*, 2015) T6 heat treatment of 6082 Al and 7075 Al series parts heated by the same induction system that Ti-6Al-4V parts performed for heat treatment. It has been determined that the production costs and energy consumption of aluminum parts change according to the production pattern. When the obtained results were evaluated, it was found that the heating and artificial aging costs per kilogram were about 0.9883 \$/kg for the 6082 Al series and 0.9183 \$/kg for the 7075 Al series, irrespective of the geometric shapes of the aluminum pieces.

Taştan *et al.* (2015) found that the cost of T6 heat treatment of Ti parts with the same induction system is about 18% lower than the heat treatment cost of Al parts when comparing the heat treatment costs of 6082 Al and 7075 Al series parts

In case of T6 heat treatment applied with aluminum samples by conventional methods, they are stored at approximately 510 °C - 540 °C for 4-6 h then artificially aged for 8-12 h at 180 °C - 200 °C with immediate watering. That is, the T6 heat treatment is completed in approximately 900 min (15 h). However, in the case of the solution taking in one minute and the aging in 8 min by induction, the heat treatment can be completed within 9 min of total induction use. It was observed that the total heat treatment time was completed within 15 min after the dissolution, water quenching and artificial aging; the sample was cooled in an open atmosphere. It has been found that the induction of T6 heat treatment results in a reduction of production costs by 2.3 times and a decrease of production times by 60 times.

4. CONCLUSIONS

In this study, 6082 Al and 7075 Al samples were subjected to T6 heat treatment at different temperatures and in different geometric shapes using

UHFIHS. The results of the obtained values are given below.

- When the production costs for 6082 Al and 7075 Al parts are examined, it is seen that the lowest cost is in the square parts and the highest cost is in the cylinder parts.
- When the manufacturing costs of 6082 Al and 7075 Al samples were compared between themselves, it was found that the 7075 Al series parts consumed about 10% less energy. In addition, when compared to the parts shapes, it can be seen that 7075 Al series parts can be heated at lower rate about 13% when it is cylinder, 10% when it is hexagonal and 8% when it is square.
- Aluminum samples with squares for both series were found to have a hardness value of about 5% greater than the cylindrical and hexagonal shapes.
- The hardness values attained by T6 heat treatment, which was completed in about 900 min (15 h) total by conventional methods for 6082 Al parts, were reached in about 9 min using UHFIHS. This demonstrates that the induction of T6 heat treatment reduces the production time by 100 times.
- On the other hand, heat treatment with the 9 minute induction for 7075 Al samples was not sufficient and the hardness value was found to be about 19% less.

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