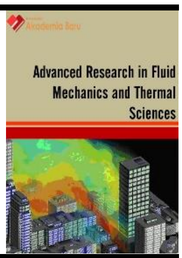
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



An Overview on Forming Process and Heat Treatments For Heat Treatable Aluminium Alloy

Open Access

Shamy Nazrein Md Yahaya[1], I. I. Azmi[1], Chuan Huat Ng[1,*], Chee Fung Lai[1], Mohd Yussni Hashim[1], A. Adam[1], R. Baehr[2], Karl Heinrich Grote[3]

[1] Advanced Forming Research Group (AFRG), Department of Manufacturing Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia
[2] Department 2Bereich Ur- und Umformtechnik, Institut fuer Fertigungstechnik und Qualitaetssicherung, Otto von Guericke University Magdeburg, Universitaetsplatz 239106 Magdeburg, Germany
[3] Lehrstuhl fuer Konstruktionstechnik, Institut fuer Machinenkonstruktion, Otto von Guericke University Magdeburg, Universitaetsplatz 2, 39106 Magdeburg, Germany

ARTICLE INFO

Article history:
Received 12 January 2020
Received in revised form 4 March 2020
Accepted 8 March 2020
Available online 24 April 2020

Keywords:
Forming process; Heat treatment; Aluminum alloy

ABSTRACT

Weight reduction and material substitution were increasing trends in the automotive industry due to the growing demand for more fuel-efficient vehicles to reduce energy consumption nowadays. The characteristic properties of aluminium alloy which includes high strength stiffness to weight ratio, good corrosion resistance, and high recycling potential make it the ideal candidate to replace the other materials (Steel or copper) currently used in cars. The replacement to aluminium alloy parts is on par to the weight reduction demand within automotive industry. The focus on lightweight had also brought the attention on the high strength Aluminium alloy. Its high mechanical properties and excellent strength to weight ratio had made it suitable for car frame parts. In order to improve its mechanical properties, the heat treatment technique make it the suitable process to implement in aluminium alloy for produce the car body parts. The process of heat treatment was same as hot stamping technique which is this process was to improve its mechanical properties. Hence, in order to define and identified the heat treatment technique available, this paper had reviewed on the development of forming process and heat treatment condition applied toward aluminium alloy throughout the years.

1. Introduction

The needs of lightweight parts within automotive and aerospace industries has been increasing tremendously especially for structural and body parts. In order to cope with challenges of having lightweight parts, aluminium alloy was introduced as based material in making all those parts. Its high strength and excellent corrosion resistance had made it to be crucial especially for industrial

* *Corresponding author.*
E-mail address: ahuat@uthm.edu.my (Chuan Huat Ng)

https://doi.org/10.37934/arfmts.70.1.112124

applications. Apart from that, other characteristic properties of aluminium such as high strength stiffness and great recycling potential make it a great candidate to replace a heavier material applied for vehicles part. However, aluminium alloy posed some issues especially in term of its formability. The material high tensile strength and hardness at tempered stage make it hard to form into desired design and shape. Hence, a forming process was proposed whereby the process will involve forming the aluminium alloy in elevated temperature. The process which was known as Hot Forming and in-Die Quenching (HFQ) have three main stages involved which includes solution heat treatment solution heat treatment stages followed by forming stages and ended with heat treatment stages. Application of high strength aluminium alloy had been regarded as one of the most promising possibilities and applying this high strength aluminium alloy provide a very positive response in many requirements [1]. The average total aluminium content per car recorded in 2012 for European cars was 140kg with analysed distribution as follows [2-4].

i. Power-train (engine, fuel system, liquid lines): 69 kg (25 components analysed) in engine block and cylinder head, transmission housings and radiators.
ii. Chassis and suspension (cradle, axle): 37 kg (17 components analysed) in wheels, suspension arms and steering system.
iii. Car body (body-in-white (BIW)), hoods, doors, wings, bumpers, and interiors): 26 kg (20 components analysed) in bonnets and doors, front structure and bumper beams.

The analysis showed how the parts were made out of aluminium material in order to reduce its weight in automotive industry. This increasing trend of weight reduction through material substitution was seen in present days and believed will keep increasing throughout the years.

2. Aluminium alloy

Aluminium alloy had high demand in the automotive industry due to its high strength to weight ratio in compare to other steels. Aluminium alloys also possess good dent resistance which provide extra benefit especially in automotive body panel applications [5]. Besides that, aluminium alloys display unique properties such as lightweight, high corrosion resistance and non-magnetic. It is an ideal material for various applications and due to these variety of properties, aluminium alloys were exponentially used in matrix composite. Apart from that, aluminium alloy was also known for its good strength, high ductility, high hardness, pressure tightness, great fluidity, and good machinability. The low density of aluminium alloy at 2.7 kgm^{-3} and high Young's modulus of about 72 GPa proved the great strength to weight ratio this material possessed. In addition, aluminium alloy high thermal conductivity of 238 $Wm^{-1}K^{-1}$, superior electrical conductivity of 37.8 $m\Omega^{-1}mm^{-2}$ and excellent inherent corrosion resistance allow this material to be applied in varied application. Besides that, aluminium melting point of 660°C, specific heat of 0.917 $Jg^{-1}K^{-1}$, and a thermal expansion of 23.8×10^{-6} K^{-1} leads to opportunity of applying this material in automotive body parts [6].

Aluminium alloys can be classified mainly into two main groups which were Wrought Alloys and Casting Alloys. This classification for both groups was depending on their alloying content such as copper, zinc, silicon, magnesium, manganese, lithium and small additions of chromium, titanium, zirconium, lead, bismuth and nickel [7]. Table 1 described the designations for the wrought aluminium alloys. There were over 300 wrought aluminium alloys types with 50 types were commonly use. They were normally identified by a four-figure system which originated in the USA and had been universally accepted throughout the world [8].

Table 1
Designation for Wrought Aluminium Alloys

Alloying Element	Series
None (99 % + Aluminium)	1XXX
Copper	2XXX
Manganese	3XXX
Silicon	4XXX
Magnesium	5XXX
Magnesium + Silicon	6XXX
Zinc	7XXX
Lithium	8XXX

Non-alloying element of wrought alloys, was designated as 1XXX with the last two digits in the designation represent the purity of the metal. The last two digits represents the decimal point of aluminium purity and expressed to the nearest 0.01 percent. The second digit in the designation indicated the modification of impurity limits. If the second digit is zero, it indicates the non-alloying aluminium having natural impurity limits or original alloy. If second digit is 1 to 9, it indicate individual impurities or alloying element [9]. Casting alloy designation possessed four numbers, with a decimal point between the third and fourth numbers and a letter preceding the numbers to indicate variations. The first three numbers indicate the alloying element, and the last or fourth number indicates the product form. Table 2 describes the designations for casting aluminium alloys [8, 10].

Table 2
Designation for Casting Aluminium Alloys

Alloying Elements	Series
Unalloyed Compositions	1XX.X
Copper	2XX.X
Silicon + Copper and/or Magnesium	3XX.X
Silicon	4XX.X
Magnesium	5XX.X
Not Used	6XX.X
Zinc	7XX.X
Tin	8XX.X
Other elements	9XX.X

As an example, series of 2XX.X designation represents the group of aluminium alloyed with copper as its alloying element. The second and third digits in the designation represents the specific alloy of the family except the series of 1XX.X due to their alloying element. 1XX.X series have no alloying element content within the aluminium [11]. So, there is no special significance to those numbers. The final digit following the decimal indicates the product form. If the last digit is zero, it represented the designation applies to a finished casting. If the last digit shows 1 or 2, it is applying to the ingot from which the casting was or will be produced (XXX.1 or XXX.2). Every numbers or digits are depending on their group or the specific alloying element that used in the aluminium [12].

3. Hot Forming and In-Die Quenching (HFQ)

This Forming aluminium alloy at elevated temperature help to increase its formability while ensuring less occurrence of spring back error. However, elevating the temperature of the alloy may lead to destruction of desirable microstructure and lead to softening (recovery and recrystallization) phenomenon [8]. In order to solve the problems, a novel process integrating hot forming and quenching known as hot forming and in-die quenching (HFQ) was developed. Reviews had shown study conducted which apply the use of HFQ in forming Aluminium Alloy 6082. The forming test was performed on the platform and experimental setup developed by engineering research centre in Harbin Institute of Technology. The sheet specimen was first heated in the furnace before being transferred to a stamping die with blank holder force of 8 die spring (≈80kN). The cooling channels created by two half molds, punch and blank-holder around forming surface by distance of 8mm. The cooling rate was about 20˚C/s without any cooling water flowing. The specimen of the experiment was cut into 240mm (length) and 120mm (width) with 19mm of down displacement of punch. The testing platform was shown in Figure 1.

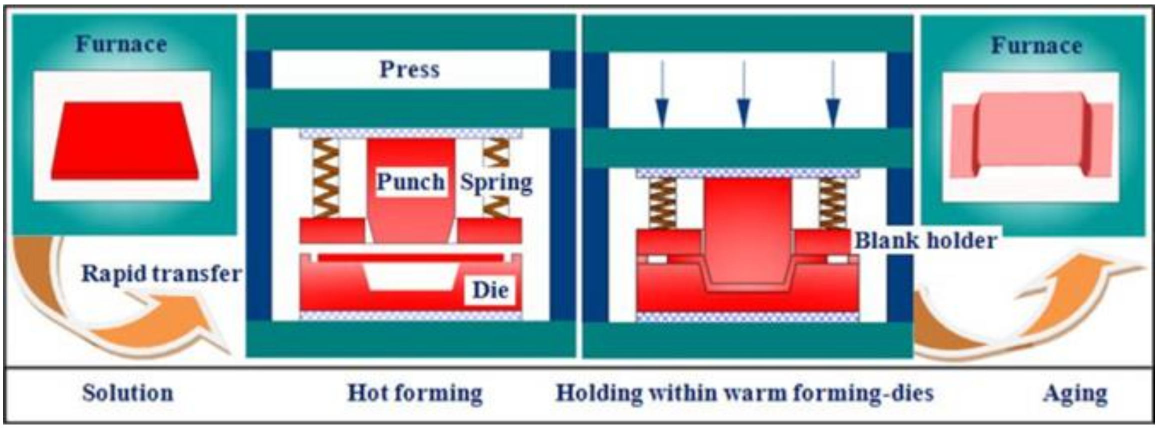


Fig. 1. Forming device for hot forming-quenching [13]

The process of Hot Forming and in-Die Quenching (HFQ) can also be applied for forming complex-shaped components in single operation. This process was a combination of forming and quenching in one stage. Within HFQ, the aluminium blank was first heated to specific temperature and kept hold within certain specific period. The fully solution heat treated aluminium blank was then transferred to a press and formed between a set of cold dies. This stage of the process was known as in-die quenching. In additions, there were two other reasons and benefit in holding the formed parts between the cold dies which includes [14]

i. Rapid quenching prevents the formation of coarse β-phase precipitates, especially at grain boundaries.
ii. Rapid quenching avoids thermal distortion of the formed part.

4. Hot Press Forming (HPF)

There were two process chain explained for Hot Press Forming which both was performed on the ultra-high strength steel (UHSS) materials known as manganese-boron steels [15-17]. The two-process chain were direct hot forming and indirect hot forming. Both of the process chain was illustrated in Figure 2. In direct hot press forming, the blank sheet was directly austenitized, transferred to the stamping tool and cooled rapidly with the forming tool while for indirect hot press forming, the blank sheet first was first formed in cold state, a process known as pre-forming stage. The blank sheet then will be put through austenitization and then transfers to calibration and quenching. This stage was the inherent stage for the process chain to ensure the required high strength properties achieved [18].

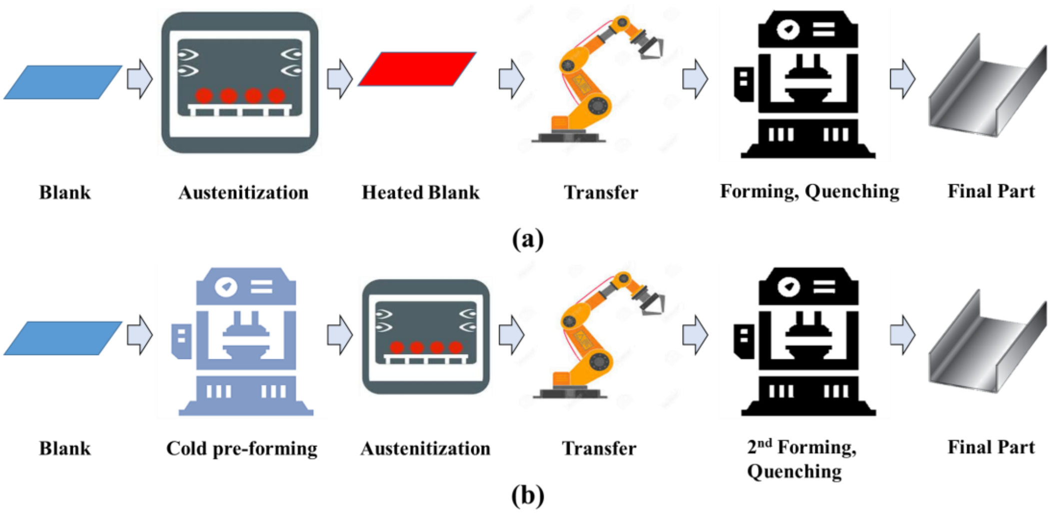


Fig. 2. Direct (a) and indirect (b) process chain in hot press forming [18]

There were three recognized ways to achieve lightweight automobile which includes optimizing vehicle frames and structures, making vehicle body out of new and alternative materials such as ultra-high strength steel to reduce the vehicle mass, and adopting advanced manufacturing techniques for automobile lightweight such as thickness-gradient high strength steel (HSS) or metal-based compound plates by hot press forming. In this paper, the author used the boron steel blank as blank material undergoing hot press forming process. The experimental procedures were as follows [19]:

i. Set different heat treatment temperature in the range of 750˚C - 1000˚C.
ii. Put the work piece into the furnace to be heated for 4 min at a certain temperature.
iii. Remove it using mechanical hand and put it into the hot forming hand moulds to be pressed quickly.
iv. Water-cooled simultaneously at cooling rate of about 30˚C/s in the mould

From this technique, the automobile weight was successfully reduced to about 30% of the total weight and able to bring out complex geometries in design without neglecting its mechanical strength [19]. Furthermore, as shown in several reviews, the advanced high strength steel was heated in a furnace to a temperature in the range of 900-950˚C. The steels were heated for 3-10 minutes in order for it to achieve full austenization. Then, this heated sheet metal was put through forming press incorporated with water-cooled dies that cool the formed blanks until the temperature reaches a temperature below the martensitic transformation finish temperature, M_f (~200°C). The required cooling rate was typically -40°Cs^{-1} to -100°Cs^{-1} [16, 20]. We may overview that Hot Press Forming (HPF) process is not that differ from Hot Forming and in-Die Quenching (HFQ) process discussed in previous sub-chapter since both processes emphasized on heat treatment which happened in the heating and quenching process.

5. Heat Treatment

Heat treatment is a process of heating and cooling of any metal which was used to alter the desired combination of mechanical properties in the metal without changing its physical shape. The change of the metal in term of mechanical properties and microstructure were due to the phase transformation and structural changes while the process of heat treatment and cooling process [21]. The factor that may change the structural and phase transformation of the metal during the heating process includes the effective quenching rate and the amount of carbon content in the element. Heat treatment is very important in altering the properties of the metal especially in term of its strength and hardness [22-24].

5.1 Solution Heat Treatment

Solution heat treatment is a process of heating the work piece material in a convection heater or furnace to dissolve the precipitates into the Al matrix. During SHT, the work piece material is kept at the desired temperature for a certain period of time to ensure that all the precipitates had fully dissolved. Longer period of soaking usually gives advantages for the formability of the material. However, for some aluminium alloys, overheating of SHT could lead to premature fracture [14]. An experiment which put the sample through full heat treatment process including Solution heat Treatment (SHT), quenching and aging were made [25-26]. The experiment was conducted on Aluminium Alloy 332 which contain 11wt% Si. This procedure was prepared accordingly and based on ASTM International B917/B917M-12 (Standard Practice for Heat Treatment of Aluminium-Alloy Castings from All Processes). The solution heat treatment process involved heating the alloy in a furnace, at 500˚C for 5 hours and then quench in water at room temperature for 1 hour. Finally, the aging process was done at same furnace at 170˚C for 2 hours [6]. The study defines the mechanical properties of the material before and after the heat treatment which shows significant improvement in term of its strength and hardness. The Aluminium Association had summarized that the most important variable affecting the mechanical properties of aluminium alloy castings (Automotive alloy parts) was heat treatment (optimum time and solution heat treatment to ensure solution of the soluble constituents). Based on the temperament of AA319 studied by a researcher which suggested heat treatments for permanent mould castings, followings overviewed were defined [27]:

i. T4-temper: Solution at 500-510˚C for 8 hours, quenching in hot water, ageing at room temperature.
ii. T5-temper: Solution at 205˚C for 7-9 hours, air cooling.
iii. T6-temper: Solution at 500-510˚C for 8 hours, quenching in hot water, reheating to 150-160˚C for 2-5 hours, air cooling.

5.2 Quenching

Quenching was a process of cooling down the metal after making the solution heat treatment. It is a rapid cooling process which can be performed by any medium such as by using the force air, water, oil, Hot Press Forming (HPF), and Hot Forming & in-die Quenching (HFQ). Different quenching medium was defined to have and possessed different rate of quenching [28]. Quenching was a critical step in the production of precipitation hardenable aluminium alloys. In most cases, the most rapid cooling from solution heat treatment was required in order to develop the best properties, but lower quench rates were seen to minimize the residual stress from the quenching operation. Other studies had shown that the purpose of quenching was to preserve the solid solution formed at the solution heat treatment temperature by rapid cooling to room temperature. The quenching rate and quenching medium were the main parameters in controlling the material mechanical properties. Besides that, the highest strength can be achieved when a material undergone high and rapid quenching rate [29]. Zhang have done a research by using water cooled die (fast cooling) to quench his specimen made of aluminium alloy 7075 in order to study the processing windows for the hot stamping of AA7075. This process was shown to ‘freeze’ the work piece material during and after forming to obtain a microstructure in a desirable super saturated solid solution (SSSS) state [28]. A quenching rate above the critical quenching rate of the work piece material was seen to be essential in order to avoid the generation of coarse precipitates on the grain boundaries, which diminishes the artificial ageing response of the work piece material. Furthermore, many researchers have selected water as the quenching medium and artificial ageing process as the further process of gaining the mechanical strength and hardness because water is cheap, readily available and nontoxic [30].

5.3 Aging

Aging is a part of heat treatment which increase the properties in different phases of material. The aging process was divided into two types which were Artificial Aging and Natural Aging. Artificial Ageing is a process of treatment of an alloy by elevated temperature to speed-up precipitation of a component from solid solution. This process was done after the process of quenching which is to alter their properties of aluminium alloy. Ahmad from University Malaysia Pahang studied on the effect of aging time on microstructure mechanical properties of AA6061 friction stir welding joints. A simple artificial aging treatment was able to enhance the tensile properties of his specimen which is 3mm plate aluminium alloy 6061. From the result, it shows an increment of tensile strength from 0.3% to 4.7% when the time of aging was increased [31]. Another aging condition which is the natural aging is a process of aging in which the specimens were put through in a room temperature for a period of time [23]. Besides that, other researcher said that in terms of experimentally point of view, the application of different artificial ageing heat treatments leads to an improvement of the mechanical properties compared with the results registered by natural ageing. The experiment was performed on the samples of ATSi6Cu4Mn aluminium alloy artificially aged by unconventional heat treatments [32]. Based on the experiment, the results highlight the improvement of the average Brinell hardness value after the process of artificial ageing compared to natural ageing. George from University Hamilton had studied the effect of ageing heat treatment on the hardness and tensile properties of aluminium A356.2 casting alloy. Based on the result, the recommendation for solution zing the components was defined to be at 540˚C for 12 hours, followed by quenching in water at 80˚C and an artificial ageing at 155˚C for various times. Within this study also, the researcher had performed the combination of process which combined the natural ageing and artificial ageing but the results of high strength and elongation were not as desired. Combination aging were proven to have its pros and cons and can affect the specimen quality [33].

Aluminium alloys properties can also be enhanced through the process of Solution Heat Treatment and aging treatment parameters. By aging the specimen at room temperature (natural aging), the mechanical properties can be stable after some days especially for AA2000 series [34]. A study had proven that by doing the aging it actually can improved the properties of alloy but will decrease the material formability properties. It depends on how the process was performed in order to make sure the formability of specimen presented in a good condition [35]. Besides, the others researcher had studied the effect of aging treatment on mechanical properties of AA6082. There were variety of aging temperature and aging time. The aging temperature was conducted at 160°C, 180°C, and 200°C with 8h, 16h, 31h, 48h, 1.5h, 3h, 32h, 30min, 2h, 6h, and 14h. The specimens were put through the SHT stage at 525°C initially followed by water quenching. The results shown, at a constant time, the stress increased and the uniform elongation decreases. The process with increasing in aging temperature in under aging condition. In contrast when the over aging occurs, the stress decreases and the uniform elongation increases [36]. In addition, the natural aging was shown to result highest in material resistivity when natural aging was conducted for 2 weeks. As the temperature of aging was set at 120°C, the resistivity of the naturally aged specimen initially increases showing direct relation between resistivity and aging time. It's also identified that when the over-aging occurred, the resistivity of the material decreases due to grain damage phenomenon. The rate of resistivity decreases during over-aging compare to resistivity during under-aging [23].

6. Mechanical Testing in Defining the Quality of Heat and Formed Aluminium Alloy

All the specimens of aluminium alloys were put through several analyses to investigate the performance after heat treatment process. Normally, after completed the heat treatment experiment, the specimens were put through mechanical testing such as tensile test and hardness test. Other than that, the specimens was also put through Optical Microscope (OM) in order to check the microstructure change after heat treatment.

6.1 Tensile Test

Tensile testing was a process that used in defining mechanical properties of material. Mechanical properties of cast component and specifically the tensile properties obtained from the test includes ultimate tensile strength (UTS), yield strength (YS) and percentage of elongation (%EI) [36]. These tensile properties were widely used in evaluating the performance of a cast component. The tensile properties can be calculated from the engineering stress-strain curve that shown in Figure 3 [37].

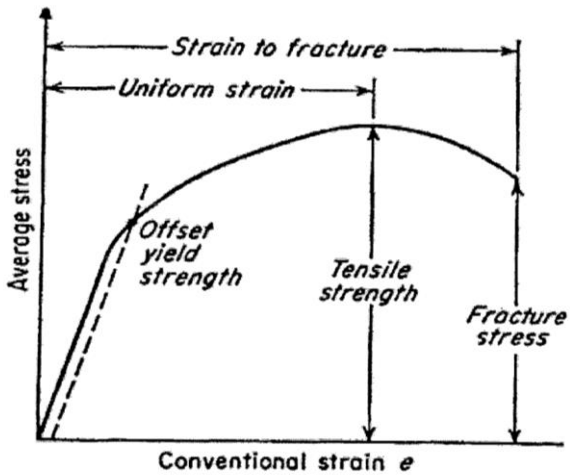


Fig. 3. The engineering stress-strain curve [37]

The stress or the average longitudinal stress along the axis can be calculated by using this equation.

$$S = {}^{P}/_{A_o} \tag{1}$$

In the equation above, P is the longitudinal load on the specimen, and A_o is the original of cross-section area of the specimen. Besides that, to find the percentage of elongation (%el) is calculated by using this equation which is

$$\%el = {}^{\Delta L}/_{L_o} \tag{2}$$

In the equation above, ΔL is the instantaneous elongation change and the L_o is the original of the length of specimen [37]. Besides that, a study on the effects of heat treatment of a 6061-aluminium alloy was overviewed. Within the study, a tensile test was performed on the specimen. The results show that the yield stresses at ambient temperature decrease if the maximum temperature increases or if the heating rate decreases [21]. The tensile test was performed at room temperature with specimens previously heated. This test to evaluate the influence of the maximum temperature and the heating rate on the strength of the material at room temperature. It shows that, at heating rate of 15 Ks^{-1} and maximum temperature of 400˚C, the yield stress will decreases if the peak temperature increases and the heating rate decreases [38].

6.2 Hardness Test

The hardness testing enables us to evaluate the strength, material properties, ductility, and wear resistance [39]. From this application of test, it can also help to determine whether a material or material treatment was suitable to be use or not. Adeyemi from Obafemi Awolowo University, Nigeria had studied the effect of heat treatment on some mechanical properties of AA7075. The specimen was put through Brinell hardness test using Houndsfield extensometer in compression mode. The specimens were polished to 600 microns and mounted on the machine using a dwell time of 15 seconds. The diameter of the impression left by the ball then was measured using Brinell calibrated hand lens and the corresponding Brinell hardness number was determined as shown in Table 3 [40].

Table 3
Results of Brinell hardness test

Sample	Hardness number (HB)
As-cast (gradually cooled)	201
As-cast (rapidly cooled)	157
Annealing	124
Age hardening	171

Besides that, others researcher also investigated of the quenching properties of selected media on 6061 Aluminium Alloy. The specimen was performed to rapid cooling of materials to room temperature. This process creates a saturated solution and allows for increased the hardness of the material. The testing operation was conducted using Rockwell hardness machine. The results obtained from Rockwell hardness test method and three indentations are presented in Figure 4 [41].

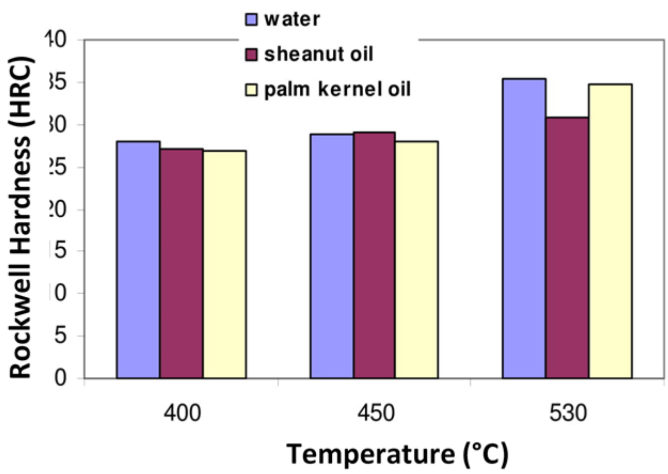


Fig. 4. Effect of temperature and quenching medium on Rockwell Hardness of AA 6061 [25]

The results of hardness of the aluminium alloy specimens that quench in water, shea nut oil and palm oil at a temperature of 530˚C were increased. This result shows a difference medium of quenching with hardness testing. Apart from that, a study by Appendino did the hardness measurement using Brinell hardness method on disc with polished surface and obtained by sectioning the bars perpendicularly to the extrusion direction. This test was performed on the material of aluminium alloy 6061 which is extruded bars (45mm in diameter). The increases in hardness for this specimen of aluminium alloy and its composite are similar if a full solution was reached [22].

A study by Ridhwan from University Technical Malaysia Malacca which perform natural aging process on aluminium alloy 6061 by different of parameters. Based on the results, the natural aging stated the highest mechanical properties in term of ultimate tensile strength and yield strength [14]. It shows the natural aging with a long time of period has the ability to achieve the higher performance of aluminium in line with the objective of aging in this experiment. The results of mechanical testing and microanalysis will determine the performance of the aluminium. Good temperature, process, and period of time and will present the best properties of aluminium alloy. Furthermore, the hot stamping process which is Hot Press Forming (HPF) have the same process chain which are heating and quenching. This method was only done on Boron steel where this process will emphasize on heat treatment towards aluminium alloy. In order to increase a production rate, a good aging in heat treatment will influenced the final formed of aluminium. This is because, as mentioned by other researcher, the aging stage is very important due to its ability to improve the mechanical properties from T6 specimen that have been through the Solution Heat Treatment Process [42].

7. Conclusions

Within all the experiment overviewed, the work pieces which were put through heat treatment and press formed shown significant improvement especially in term of its mechanical strength. The future of lighter and higher fuel efficient automotive was seen to be bright and on track. Several overviews were observed and defined and listed as follows.

i. Press forming technique of Hot Forming and in-die Quenching (HFQ) and Hot Press Forming (HPF) were both overviewed. Both the technique possessed similar stages but performed on two different materials. HFQ was performed toward aluminium alloy while HPF was performed toward boron steel. Potential of forming aluminium alloy using HPF process was seen and defined to be highly possible.
ii. Material heat treatment need to be done efficiently at exact time and temperature. A setup with wrong period and temperature may cause over aging hence damaging the material.
iii. The testing of tensile test and hardness test is a great way in defining the quality of the final heat-treated parts and press formed parts. The testing is important in order to make sure that the material achieved the desired final properties before being applied for consumer use.

Acknowledgement
The authors would like to acknowledge the Universiti Tun Hussein Onn Malaysia for the support and help throughout the study. Special acknowledge goes to the Research Management Center and Ministry of Education Malaysia for funding this study under Fundamental Research Grant Scheme (FRGS K053), Tier 1 Grant (H137) and GPPS (H275).

References

[1] Henriksson, Fredrik, and Kerstin Johansen. "On Material Substitution in Automotive BIWs–From Steel to Aluminum Body Sides." *Procedia CIRP* 50 (2016): 683-688. https://doi.org/10.1016/j.procir.2016.05.028
[2] Ng, Chuan Huat, Shamy Nazrein Md Yahaya, Chee Fung Lai, Faizal Sharrifuddin, and Karl Heinrich Grote. "Reviews on the Forming Process of Heat Treatable Aluminium Alloys." *International Journal of Integrated Engineering* 10, no. 5 (2018). https://doi.org/10.30880/ijie.2018.10.05.012
[3] Mori, Ken-ichiro, P. F. Bariani, B-A. Behrens, A. Brosius, S. Bruschi, T. Maeno, M. Merklein, and J. Yanagimoto. "Hot stamping of ultra-high strength steel parts." *CIRP Annals* 66, no. 2 (2017): 755-777. https://doi.org/10.1016/j.cirp.2017.05.007
[4] Moons, Theo, Petar Ratchev, B. Verlinden, P. Van Houtte, and P. De Smet. "A comparative study of two Al-Mg-Si alloys for automotive applications." *Scripta Materialia* 35, no. 8 (1996). https://doi.org/10.1016/1359-6462(96)00244-8
[5] Garrett, R. P., J. Lin, and Trevor A. Dean. "Solution heat treatment and cold die quenching in forming AA 6xxx sheet components: feasibility study." In *Advanced materials research*, vol. 6, pp. 673-680. Trans Tech Publications Ltd, 2005. https://doi.org/10.4028/www.scientific.net/AMR.6-8.673
[6] Zainon, F. I. Z. A. M., Khairel Rafezi Ahmad, and R. U. S. L. I. Z. A. M. Daud. "Effect of Heat Treatment on Microstructure, Hardness and Wear of Aluminum Alloy 332." In *Applied Mechanics and Materials*, vol. 786, pp. 18-22. Trans Tech Publications Ltd, 2015. https://doi.org/10.4028/www.scientific.net/AMM.786.18
[7] Miller, W. S., L. Zhuang, J. Bottema, A_J Wittebrood, P. De Smet, A. Haszler, and Ai Vieregge. "Recent development in aluminium alloys for the automotive industry." *Materials Science and Engineering: A* 280, no. 1 (2000): 37-49. https://doi.org/10.1016/S0921-5093(99)00653-X
[8] Kaufman, J. Gilbert. "Understanding wrought and cast aluminum alloy designations." ASM International, 2000, p 23-37, 2013.
[9] Ibrahim, Mohamed Fawzy. "Effects of Be, Sr, Fe and Mg interactions on the microstructure and mechanical properties of aluminum based aeronautical alloys." PhD diss., Université du Québec à Chicoutimi, 2015.
[10] J.R. Davies. "Aluminium and aluminium alloys. " ASM international, 1993.
[11] De Matteis, Gianfranco, Giuseppe Brando, and Federico M. Mazzolani. "Pure aluminium: An innovative material for structural applications in seismic engineering." *Construction and Building Materials* 26, no. 1 (2012): 677-686. https://doi.org/10.1016/j.conbuildmat.2011.06.071
[12] Ismail, A., and M. S. Mohamed. "Review on sheet metal forming process of aluminium alloys." In *The International Conference on Applied Mechanics and Mechanical Engineering*, vol. 17, no. 17th International Conference on Applied Mechanics and Mechanical Engineering, pp. 1-13. Military Technical College, 2016. https://doi.org/10.21608/amme.2016.35204
[13] Fan, Xiaobo, Zhubin He, Shijian Yuan, and Peng Lin. "Investigation on strengthening of 6A02 aluminum alloy sheet in hot forming-quenching integrated process with warm forming-dies." *Materials Science and Engineering: A* 587 (2013): 221-227. https://doi.org/10.1016/j.msea.2013.08.059
[14] Jumaidin, Ridhwan, Iffa Marina Jopri, Rafidah Hasan, and Muhammad Ilman Hakimi Chua. "Effect of Cooling Medium and Tempering on Microstructures and Hardness of SK3 High Carbon Steel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 63, no. 2 (2019): 199-209.
[15] Kumar, B. Senthil, and Subramanian Balachandar. "A study on the influence of hot press forming process parameters on Flexural Property of Glass/PP Based Thermoplastic Composites Using Box-Behnken Experimental Design." *ISRN Materials Science* 2014 (2014). https://doi.org/10.1155/2014/624045
[16] Fan, Dong W., Han S. Kim, and Bruno C. De Cooman. "A review of the physical metallurgy related to the hot press forming of advanced high strength steel." *Steel Research International* 80, no. 3 (2009): 241-248.
[17] Fan, D. W., Han S. Kim, S. Birosca, and B. C. De Cooman. "Critical review of hot stamping technology for automotive steels." *MATERIALS SCIENCE AND TECHNOLOGY-ASSOCIATION FOR IRON AND STEEL TECHNOLOGY-* 1 (2007): 98.
[18] Ng, C. H., C. F. Lai, S. N. M. Yahaya, S. Shamsudin, S. N. A. S. Ahmad, and F. Sharrifuddin. "Effect of initial blank temperature in hot press forming towards 22MnB5 springback failure." *Journal of Mechanical Engineering and Sciences* 13, no. 2 (2019): 5137-5149.
[19] Chang, Ying, Zhao-huan Meng, Liang Ying, Xiao-dong Li, Ning Ma, and Ping Hu. "Influence of hot press forming

techniques on properties of vehicle high strength steels." *Journal of Iron and Steel Research International* 18, no. 5 (2011): 59-63.
https://doi.org/10.1016/S1006-706X(11)60066-6

[20] Åkerström, Paul, and Mats Oldenburg. "Austenite decomposition during press hardening of a boron steel—Computer simulation and test." *Journal of Materials Processing Technology* 174, no. 1-3 (2006): 399-406.
https://doi.org/10.1016/j.jmatprotec.2006.02.013

[21] Ma'at, Norzarina, MK Mohd Nor, Choon Sin Ho, N. Abdul Latif, Al Emran Ismail, K. A. Kamarudin, S. Jamian, M. N. Ibrahim, and M. K. Tamrin. "Effects of temperature and strain rates on the mechanical behaviour of commercial aluminium alloy AA6061." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 54, no. 2 (2019): 185–190.

[22] Maisonnette, D., M. Suery, D. Nelias, P. Chaudet, and T. Epicier. "Effects of heat treatments on the microstructure and mechanical properties of a 6061 aluminium alloy." *Materials Science and Engineering: A* 528, no. 6 (2011): 2718-2724.
https://doi.org/10.1016/j.msea.2010.12.011

[23] Esmaeili, S., D. J. Lloyd, and W. J. Poole. "Effect of natural aging on the resistivity evolution during artificial aging of the aluminum alloy AA6111." *Materials Letters* 59, no. 5 (2005): 575-577.
https://doi.org/10.1016/j.matlet.2004.10.052

[24] Kessler, O., R. von Bargen, Fabian Hoffmann, and H. W. Zoch. "Continuous Cooling Transformation (CCT) Diagram of Aluminium Alloy Al-4.5 Zn-1Mg." In *Materials science forum*, vol. 519, pp. 1467-1472. Trans Tech Publications Ltd, 2006.
https://doi.org/10.4028/www.scientific.net/MSF.519-521.1467

[25] Andreatta, F., H. Terryn, and J. H. W. De Wit. "Corrosion behaviour of different tempers of AA7075 aluminium alloy." *Electrochimica acta* 49, no. 17-18 (2004): 2851-2862.
https://doi.org/10.1016/j.electacta.2004.01.046

[26] Engler, Olaf, and Ole Runar Myhr. "Effect of Natural Ageing on Strength and Anisotropy in Aluminium Alloy AA 6005C." In *Materials Science Forum*, vol. 877, pp. 688-694. Trans Tech Publications, 2017.
https://doi.org/10.4028/www.scientific.net/MSF.877.688

[27] Gauthier, J., P. R. Louchez, and F. H. Samuel. "Heat treatment of 319.2 aluminium automotive alloy Part 1, Solution heat treatment." *Cast Metals* 8, no. 2 (1995): 91-106.
https://doi.org/10.1080/09534962.1995.11819197

[28] Staley, J. T. "Quench factor analysis of aluminium alloys." *Materials Science and Technology* 3, no. 11 (1987): 923-935.
https://doi.org/10.1179/mst.1987.3.11.923

[29] Bardelcik, Alexander, Christopher P. Salisbury, Sooky Winkler, Mary A. Wells, and Michael J. Worswick. "Effect of cooling rate on the high strain rate properties of boron steel." *International Journal of Impact Engineering* 37, no. 6 (2010): 694-702.
https://doi.org/10.1016/j.ijimpeng.2009.05.009

[30] Fakioglu, Avni, Dursun Özyürek, and Ramazan Yilmaz. "Effects of different heat treatment conditions on fatigue behavior of AA7075 alloy." *High Temperature Materials and Processes* 32, no. 4 (2013): 345-351.
https://doi.org/10.1515/htmp-2012-0146

[31] Ahmad, R., and M. B. A. Asmael. "Effect of aging time on microstructure and mechanical properties of AA6061 friction stir welding joints." *International Journal of Automotive and Mechanical Engineering* 11 (2015): 2364-2372.
https://doi.org/10.15282/ijame.11.2015.17.0198

[32] Smeadă, Mihaela, Maria Stoicănescu, Irinel Radomir, and Lucica Geamăn. "Artificial ageing of aluminum alloys. Statistical studies of results." *Procedia-Social and Behavioral Sciences* 62 (2012): 881-885.
https://doi.org/10.1016/j.sbspro.2012.09.148

[33] Y-D. Li, J-L Suo, Guangli Bi and T-J Chen. "Effects of heat treatment on microstructure and mechanical properties of rheo-diecasting 2024 wrought aluminum alloy," *Chinese Journal of Nonferrous Metal,* vol. 24, no. 4, pp. 894–904, 2014.

[34] Verlinden, Bert, P. Wouters, H. J. McQueen, Etienne Aernoudt, Lucas Delaey, and S. Cauwenberg. "Effect of different homogenization treatments on the hot workability of aluminium alloy AA2024." *Materials Science and Engineering: A* 123, no. 2 (1990): 229-237.
https://doi.org/10.1016/0921-5093(90)90288-E

[35] Fan, Xiaobo, Zhubin He, Shijian Yuan, and Peng Lin. "Investigation on strengthening of 6A02 aluminum alloy sheet in hot forming-quenching integrated process with warm forming-dies." *Materials Science and Engineering: A* 587 (2013): 221-227.
https://doi.org/10.1016/j.msea.2013.08.059

[36] Anjabin, N., and Karimi Taheri. "The effect of aging treatment on mechanical properties ofaa6082 alloy: modelingand experiment." *Iranian Journal of Materials Science and Engineering* 7, no. 2 (2010): 14-21.
[37] Liu, George Y. "Effect of ageing heat treatment on the hardness and tensile properties of aluminum A356. 2 casting alloy." PhD diss., 2009.
[38] Isadare, Adeyemi Dayo, Bolaji Aremo, Mosobalaje Oyebamiji Adeoye, Oluyemi John Olawale, and Moshood Dehinde Shittu. "Effect of heat treatment on some mechanical properties of 7075 aluminium alloy." *Materials Research* 16, no. 1 (2013): 190-194. https://doi.org/10.1590/S1516-14392012005000167
[39] Kazeem, Abubakar, Nur Azam Badarulzaman, and Wan Fahmin Faiz Bin Wan Ali. "Effect of Isothermal Heat Treatment on Hardness of X7475 Aluminium Alloys." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 55, no. 2 (2019): 233-239.
[40] Isadare, Adeyemi Dayo, Bolaji Aremo, Mosobalaje Oyebamiji Adeoye, Oluyemi John Olawale, and Moshood Dehinde Shittu. "Effect of heat treatment on some mechanical properties of 7075 aluminium alloy." *Materials Research* 16, no. 1 (2013): 190-194. https://doi.org/10.1590/S1516-14392012005000167
[41] Abubakre, O. K., U. P. Mamaki, and R. A. Muriana. "Investigation of the quenching properties of selected media on 6061 aluminum alloy." *Journal of Minerals & Materials Characterization & Engineering* 8, no. 4 (2009): 303-315. https://doi.org/10.4236/jmmce.2009.84027
[42] Emani, S. V., J. Benedyk, P. Nash, and D. Chen. "Double aging and thermomechanical heat treatment of AA7075 aluminum alloy extrusions." *Journal of materials science* 44, no. 23 (2009): 6384-6391. https://doi.org/10.1007/s10853-009-3879-8