# Warm forming of High-strength Aluminum alloys for the Automotive industry

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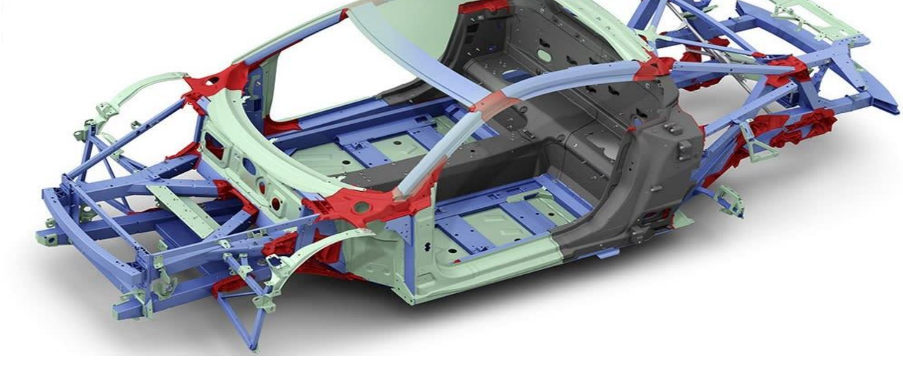

# Abstract

The aim of this thesis is to give a brief overview of some experiments on the high-strength aluminum alloys of the 6xxx and 7xxx series and to analyse their main mechanical properties in the light of the test results. Firstly, a literature presentation on aluminum, aluminum alloys and their warm forming is given, followed by an overview of the current applications (with emphasis on the automotive sector), properties and problems of aluminum alloys. In the next sections, which form the main part of this report, suitable thermoformable aluminum alloys AA6016, AA7021 and AA7046 are selected for detailed experimental descriptions, showing the results of individual experiments including data and figures, including tensile tests, hardness tests, metallography and finally conclusions are drawn.

**Keywords:** Aluminum alloy, warm forming, mechanical properties, automotive manufacturing

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I would like to thank all the staff members of Politecnico di Torino who have helped me during the completion of my thesis.

My thesis was completed during the pandemic, the tragedies caused by local wars on the European continent are equally sympathetic. I wish the world peace and health.

When I finish my thesis, it will be the end of my almost 7 years of study in Turin, Italy, thanks to this beautiful city and this lovely country, and thanks to all my professors and classmates during my undergraduate studies and also during my postgraduate studies.

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# 1. INTRODUCTION OF ALUMINUM AND ALUMINUM ALLOY

## 1.1 Aluminum

Aluminum (Al) is an essential element of modern life. Almost everyone uses aluminum on a daily basis. Aluminum, a silvery-white metal, is the most widely distributed metal on Earth, making up about 8% of the Earth's core mass and is the third most common chemical element on the planet. The chemical properties of aluminum are briefly organized in Table 1. The only crystal structure of aluminum is the face-centered cubic structure.

**Table 1**

| Atomic number | Atomic weight | Density | Melting point | Boiling point | Isotopes |
|---|---|---|---|---|---|
| 13 | 16.9815386 | 2.7 g/cc | 660.32 DC | 2519 | 3 |

Aluminum has several distinctive properties:

1. it is one of the lightest metals in the world: it is almost three times lighter than iron (one third as steel);
2. it is also very strong and durable, not at all inferior to steel in durability but not in strength;
3. some alloys are ductile and easy to work with some alloyare;
4. it is resistant to corrosion because its surface is always covered with a very thin but very strong oxide film;
5. it does not magnetize, a very good conductor of electricity;

Lightweight, durable and functional: these qualities make aluminum one of the key engineering materials of our time. We can find aluminum in the homes we live in, in the cars we drive, in the trains and planes that take us on long journeys, in the cell phones and computers we use every day, on the shelves inside our refrigerators, and in modern furniture.

There are economic, social and environmental benefits associated with the use of aluminum throughout the life cycle of any transportation vehicle. Social and environmental benefits. Aluminum is light, and it ensures and often improves safety. It can be recycled from one generation to another and retains its value and characteristics after recycling. In addition, aluminum also is one of the most recycled and recyclable materials in use today, according to the statistical report of the

Aluminum Association of America. Recycled aluminum accounts for almost 80% of US aluminum production and saves the US $800 million annually [1].

Based on his various benefits, aluminum has been used in basically every field, aluminum is all around us in modern construction, automotive, aviation, energy, food and other industries. Moreover, aluminum has become a symbol of progress: many cutting-edge equipment and vehicles are made of aluminum. If all the copper wires in cars were replaced by aluminum zirconium wires, a weight saving of 30 % is possible [2].

But aluminum production requires a lot of electricity, with a yield of about 15 megawatt hours per ton. This is roughly equivalent to the consumption of a 100-unit apartment building for one month. Therefore, the best site for an aluminum smelter is near a strong and preferably renewable energy source. The aluminum industry is very conscious of the environmental impact of its activities. The mining and smelting of aluminum, plus the disposal of red mud can have a major environmental impact if not done properly. The industry is proud of its efforts and achievements in restoring open pit mining areas and restoring the flora and fauna of these sites. These efforts have been rewarded by the United Nations Environment Program and the red mud disposal areas are now being successfully revegetated. Hydroelectric plants are the one best choice because they are the most powerful "green" energy source available today.


Figure 1: Aluminum in our life

## 1.2 Aluminum alloys and their heat treatment

First, let's understand what an "alloy" is, which is a mixture of different metallic elements that are often used to enhance the strength and durability of a material. While aluminum has some amazing properties as a pure element, it may not be strong enough to achieve high durability. Therefor it can be combined with other elements to form alloys that are exponentially more durable and suitable for industrial applications. Therefor aluminum alloys are alloys with aluminum (Al) as the main metal. Typical alloying elements are copper, magnesium, manganese, silicon, tin and zinc, depending on the desired application. With the right combination of elements, aluminum can gain more strength and may even outperform steel. Alloys offer almost the same benefits as pure aluminum, and they are also relatively cost effective because of their lower melting point. In addition to being extremely strong, aluminum alloys, especially when magnesium is involved, are non-flammable and less prone to corrosion than other alloys. For these reasons of their incredible versatility, robustness and reliability, aluminum alloys are very popular in engineering, construction, aerospace and automotive applications.

Aluminum alloys can be divided into two categories by processing method, namely wrought aluminum alloys and cast aluminum alloys. Further distinctions in each category are based on the primary mechanisms of property development and so can be further subdivided into heat treatable and non-heat treatable categories. Specific operations can be used to improve the strength and hardness of precipitation-hardenable wrought and cast alloys, which are called "heat treatable" alloys, while those that cannot be significantly strengthened by heating and cooling are called "non-heat treatable" alloys and are used only in as-cast or thermally modified conditions unrelated to solution or precipitation effects [3]. Heat treatment is used to alter the microstructure of metals and alloys to make the metal stronger or more ductile, more resistant to wear or more ductile, to impart properties that benefit the life of the part, such as increased surface hardness, temperature resistance, ductility and strength. It is a key step in the aluminum manufacturing process to achieve the desired end-use properties. Heat treatment to increase strength of aluminum alloys is a three-step process: 1. Solution heat treatment: dissolution of soluble phases; 2. Quenching: development of supersaturation; 3. Age hardening: precipitation of solute atoms either at room temperature (natural aging) or elevated temperature (artificial aging or precipitation heat treatment) [3]. The first step is an elevated temperature process designed to dissolve the soluble eutectic components and convert them into a solid solution; the second step is to prevent or retard immediate reprecipitation by rapid quenching, usually in water, which can make the alloy very workable in a short time. All heat treatments involve heating and cooling the metal, but there are three main differences in the process: heating temperature, cooling rate and type of quench, which are used to achieve the desired properties. The third step is what we often call aging, which can be divided into two categories. After a period of several days at room temperature, called natural aging, the strength of the alloy is greatly increased. Heating at high temperatures for a controlled period of time, a process known as artificial aging or precipitation hardening. The precipitates formed and grown by artificial aging are more controlled and appreciable in nature and have higher mechanical properties compared to natural aging conditions. As the AA7XXX series is the most popular high-strength aluminum alloy, many studies have focused on the heat treatment process. For example, Suleiman E. Al-lubani et al. studied the heat treatment of AA7449 in 2015 [4] and R. RANGANATHA1 et al. studied the multi-step heat treatment of AA7049 in 2013. [5]. Moreover, in this study, we also set up a control group of "pre-aged" and "no pre-aged" to observe the effect of the third step of different heat treatments on the warm forming of aluminum alloys.

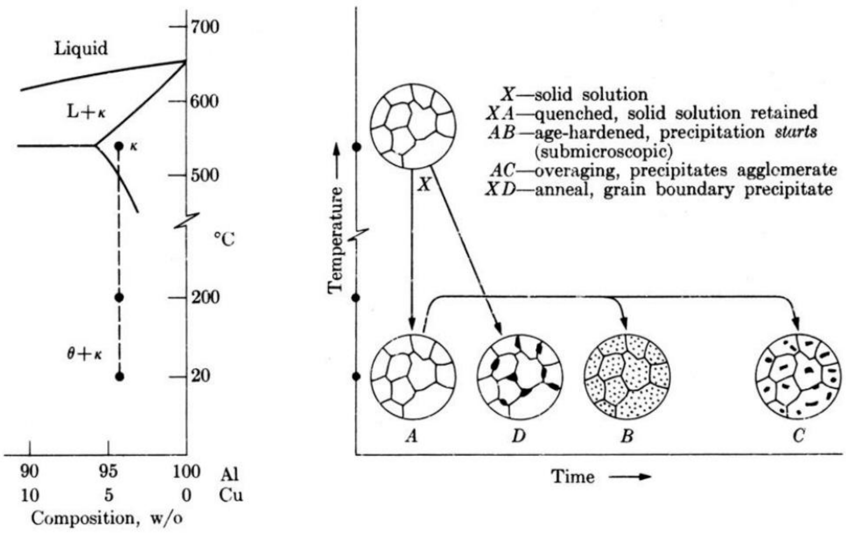



Figure 2: heat treatment process

The aluminum alloy is indicated by four numbers, which includes the proportion of alloy composition. A dash is also used after the 4-digit number to indicate the type of heat treatment, for example, "6061-T6". Currently, the International Alloy Designation System (IADS) is widely accepted for naming forged alloys. Each alloy is due to a four-digit number, where the first digit is the major alloying element. The following tables (table 2 for cast aluminum alloy and table 3 for wrought aluminum alloy) is a compilation of the naming of aluminum alloys.

**Table 2 Cast aluminum alloys use the 4-digit system but includes a decimal point (XXX.X). The first digit indicates the major alloying element or elements.**

| ALLOY | MAIN ALLOYING ELEMENT |
|---|---|
| 1XX.X | Pure Aluminum |
| 2XX.X | Copper |
| 3XX.X | Silicon and/or Copper and/or Magnesium |
| 4XX.X | Silicon |
| 5XX.X | Magnesium |
| 6XX.X | Not used |
| 7XX.X | Zinc |
| 8XX.X | Tin |
| 9XX.X | Other |

**Table 3 Wrought aluminum alloys also use the 4-digit system (XXXX). The first digit is also used to indicate the primary alloying element.**

| ALLOY | MAIN ALLOYING ELEMENT |
|---|---|
| 1XXX | Pure Aluminum |
| 2XXX | Copper |
| 3XXX | Magnesium |
| 4XXX | Silicon |
| 5XXX | Magnesium |
| 6XXX | Magnesium and Silicon |
| 7XXX | Zinc |
| 8XXX | Other |

However, as mentioned before, not all aluminum alloys can be strengthened by heat treatment: aluminum alloys can be divided into two categories: heat treatment strengthened and non-heat treatment strengthened. Aluminum alloys that cannot be strengthened by heat treatment are those aluminum alloys whose mechanical properties cannot be significantly improved by heat treatment, and whose solid solution composition does not change with temperature and cannot be strengthened by solid solution treatment (like AA1XXX, AA3XXX, AA4XXX and AA5XXX). Whether an aluminum alloy can be strengthened by heat treatment depends on the nature and content of alloying elements.

The main aluminum alloy heat treatment methods and designation system is shown in the table 4.

**Table 4: The designation system is used for all forms of wrought aluminum and aluminum alloys.**

| TEMPER DESIGNATION | HEAT TREATMENT |
|---|---|
| **F** | As fabricated |
| **O** | Annealed (to obtain the lowest strength temper) |
| **W** | Solution heat treated (unstable temper) |
| **H** | Strain-hardened (cold worked after annealing) |
| **T** | Heat treated to produce stable tempers other than F, O, or H. |

T-temper is the method of heat treatment used for the samples in our current study (T6 and T4, respectively).

T4: Solution heat treated and naturally aged to a stable condition

T6: Solution heated and artificially aged to maximum strength

We know that the 6xxx series (Al-Mg-Si) alloys have good formability, weldability, machinability and corrosion resistance, and are moderately strong. Alloys in this heat-treatable group may be formed in the T4 temper (solution heat treated but not precipitation heat treated) and strengthened after forming to full T6 properties by precipitation heat treatment [6]. Since these alloys are typically used under heat treatment conditions, the addition of the major alloying elements in this series does not have a detrimental effect, but rather is intended to control the grain structure. It should be noted that at copper levels higher than 0.5% some intergranular corrosion can occur in some tempers (e.g., T4 and T6) [6]. The figure 3 shows the relationship between some of the more commonly used alloys in the 6xxx series.

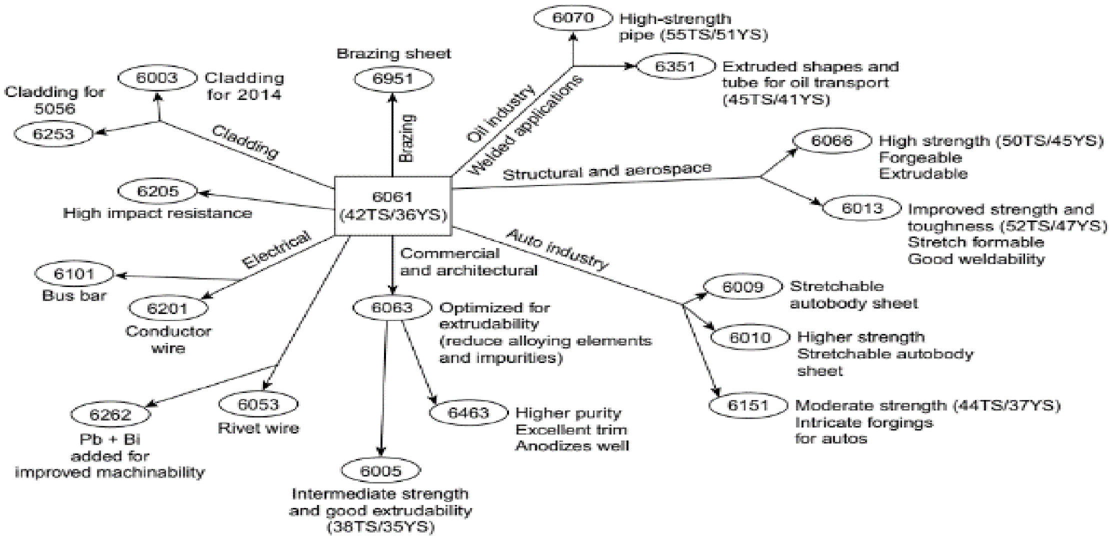



Figure 4: Common aluminum alloy of 6xxx series

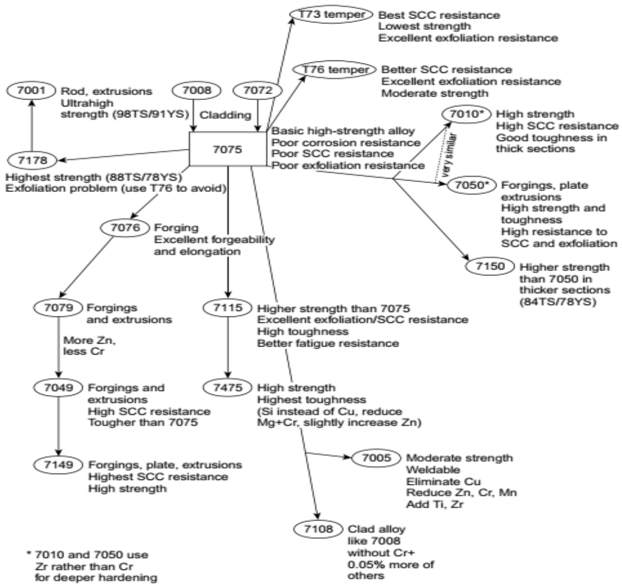



Figure 3: Common aluminum alloy of 7xxx series

We know that the main alloying element in the 7xxx series of alloys is zinc at 1-8% and when combined with magnesium and copper (or no copper), a very high strength heat treatable alloy is produced. But often other elements, such as manganese and chromium, are added in small amounts7xxx series alloys are now commonly used in aircraft/automotive fuselage structures, mobile equipment and other high stress components. However, the higher strength 7xxx alloys exhibit reduced resistance to stress corrosion cracking and are often used in slightly overaged to provide a better combination of strength, corrosion resistance and fracture toughness. The copper-free 7XXX alloy has also received a lot of attention because of its desirable properties: moderate-to-high strength; excellent toughness; and good workability, formability, and weldability [6]. Stress corrosion cracking (SCC) is a drawback of the AA7XXX series that requires special attention. Resistance to corrosion and SCC are usually improved by faster quenching rates; however, the resistance to SCC of certain copper-free 7XXX alloys is actually improved by slow quenching [7]. The figure shows the relationship between some of the more commonly used alloys in the 7xxx family.

### 1.3 Aluminum alloys in automative field

In recent years, the greenhouse effect is getting more and more attention, and almost every government is or has made new policies and decrees to try to stop the rapid rise of carbon dioxide emissions and strive to reach carbon neutrality and save the earth as soon as possible, and the energy emission of automobiles is a point that we need to pay special attention to. Among the many ways to save energy in automobiles, automotive light weighting technology is the most important, simple and effective method for sustainable development of the automotive industry, which can improve fuel economy and reduce exhaust emissions. The European automotive industry has more than doubled the average amount of aluminum used in passenger cars during the last decade (Figure 5) and will do even more so in the coming years. In the year 2000 an average of 102kg aluminum was used in automotive parts in Western Europe, with 59kg in engine parts, 11kg in structural parts, 6kg chassis applications and 5kg for body-in-white (21 kg others) [8]. Among all the materials available for automotive applications, aluminum alloy is undoubtedly a good compromise between cost and weight reduction. Aluminum alloys are widely used for automotive light weighting due to their low density, good corrosion resistance and easy processability (as mentioned earlier).

The European Union has made a new unanimous decision to ban the sale of fuel cars in 2035, and sales of electric and hybrid vehicles will inevitably surge. China is also strongly supporting the development of new energy vehicles, setting a target of 20% of car sales by 2025. According to metals consulting firm CRU, demand for aluminum for electric and hybrid vehicles will increase tenfold to nearly 10 million tons by 2030. Given that all future vehicles will need to meet stringent emissions standards, reducing their weight is the best way to achieve this goal. Generally a 10%

mass reduction results in a 5'7% fuel consumption reduction (depending on the drive cycle), if a powertrain is downsized for constant acceleration performance [9]. Increase the use of aluminum alloys is one of the best ways to do so. Figure 5 illustrates the use of aluminum alloys in automobiles as compiled by Ducker Worldwide.

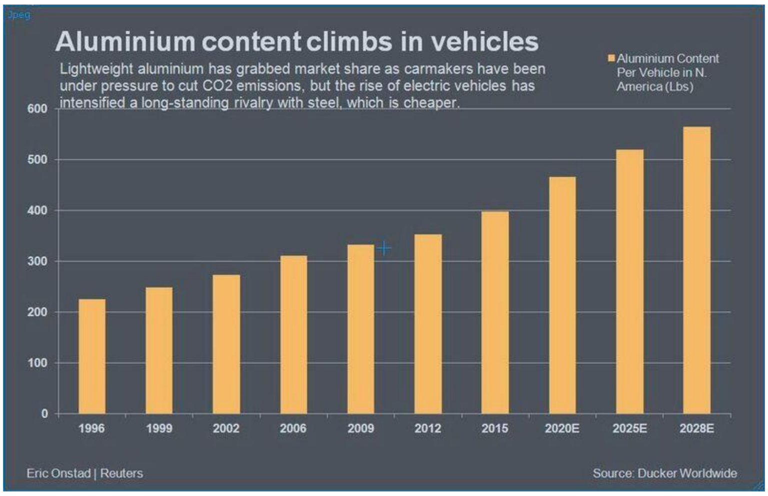



Figure 5: Latest Trends for Aluminum Demand in Automotive Industry (Image courtesy of Ducker Worldwide)

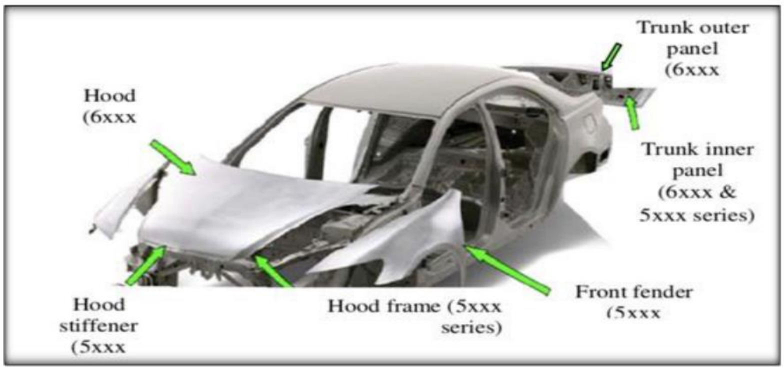



Figure 6: the typical applications of different alloys in a vehicle

The main aluminum alloy categories for automotive sheet applications are the non-heat treatable Al-Mg (EN 5xxx series) and the heat treatable Al-Mg-Si (EN 6xxx series) alloy systems, e.g. AA5754 (Al-Mg), which are widely used in body interior structures to compensate for the lack of strength. The strengthening mechanism for this alloy is strain hardening, usually by cold working during the manufacturing process, coupled with solution hardening. As a result, AA5xxx sheet components are

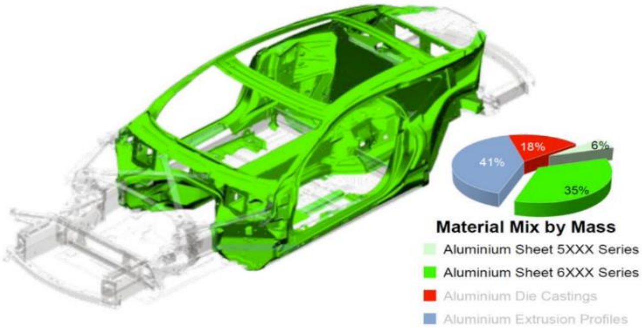



Figure 7: AA5xxx and AA6xxx series in vehicle

typically cold stamped under annealed (O), fabricated (F) or strain hardened (H) conditions with greater ductility [10]. Whereas 6xxx aluminum alloys are preferred by many automotive manufacturers for their good plasticity and high strength, as shown in Table 3, the main elements of the alloys belonging to the 6xxx series are silicon and magnesium. The ratios are approximately the same as those required to form magnesium silicide (Mg2Si), thus making them heat treatable. 6xxx series alloys have good formability, weldability, machinability and corrosion resistance with moderate strength. The presence of silicon is important because it tends to precipitate in the form of intermetallic compounds with magnesium: thus, the 6xxx series is strengthened by precipitation. These heat treatable alloys can be formed in T4 tempering (solution heat treatment, but not precipitation heat treatment) and strengthened to full T6 properties by precipitation heat treatment after forming. Among them, 6016 aluminum sheets have good forming and bake hardening properties and is widely used for hood panels, doors, trunk lids, roof panels and other components. It is a special kind of aluminum body panel. One of the samples we used in this study is AA6016 from the 6xxx series. According to a study, the weight of a car using 6016 alloy sheet is significantly lower than that of a traditional steel material, with an overall weight reduction of nearly 50 kg [11]. The Audi A8 sedan also uses 6016 alloy sheet as its outer body panel, and because of the relatively low sensitivity of AA6016 to quenching, it is produced using a water quenching process. In Europe, AA6016 is preferred and applied in gauges of around 1-1.2 mm. It shows a superior formability, better filiform corrosion resistance than the higher copper alloys, and allows flat hem s even on parts with local pre-deformation. In recent years there has also been some research involving hemming and surface texturing to optimize the overall performance of AA6016 type aluminum body panel products. The main problem with aluminum sheet bending is the formation of cracks in the hemmed radius. With improvements, it is now possible to achieve a flat hem joint in

1.2 mm AA6016 with 10% pre-strain [12].

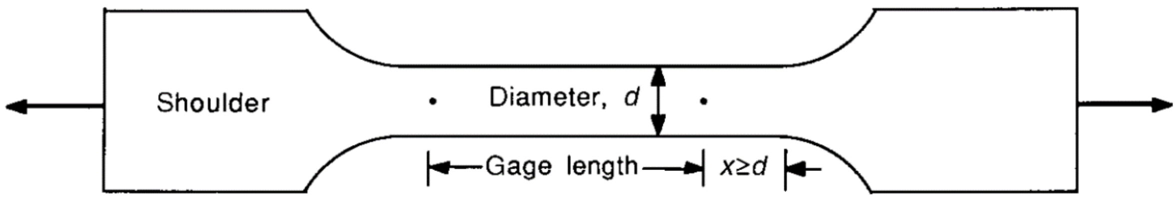
Due to the low strength of AA6XXX series, it is difficult to realize the light weight of side impact beams and A-pillar and B-pillar load-bearing structural parts. Therefore, from the consideration of service safety, high strength 7000 series aluminum alloys (Al-Zn-Mg-Cu) are becoming more and more popular among OEMs, and their high strength can meet the strength requirements of automotive load-bearing structural members, but the application of high strength AA7XXX series in automotive is still limited.

Those alloys containing copper have the highest strength and have been used as construction materials, primarily for aircraft, for over 50 years. For the aircraft industry, AA7xxx and AA2xxx are prime candidates because of their high strength and good corrosion resistance. the corrosion resistance of AA7xxx is poor at peak strength at T6 conditions, which leads to the use of such alloys in overage applications such as T73. The main alloying elements of AA7XXX are zinc, magnesium and copper these elements produce very complex precipitation phenomena resulting in high aging potential. Among commercial aluminum alloys, the 7xxx series alloys (Al-Zn-Mg-Cu) are considered excellent candidates for heavy-duty automotive structural applications because of their high strength-to-weight ratio, good ductility, and excellent corrosion resistance in most environments. However, Mg and the heavy alloying elements such as Zn in order to improve the mechanical strength of the material leads to brittleness and microstructural defects, which not only make it difficult to obtain good mechanical properties and performance, but also make it difficult to cast near-net-shape components and even more difficult to form (the uniform elongation is only about 10%, so the formability at room temperature is limited, which is the main reason for their low use in the automotive industry so far, which makes it difficult to apply the material in conventional cold forming processes(Warm forming processes are therefore expected to solve this problem). But it offers high mechanical properties - about 600 MPa compared to 300 MPa for the 6000 series - and allows automakers to further reduce weight. For example, Aleris International, Inc. has shown in its demonstrations that using 3.5 mm thick 7000 series aluminum alloys to make struts provides the same crash safety characteristics as using 2 mm corrugated UHS steel, but with a 40 percent weight reduction. A growing number of automotive companies are considering their use in future models.

In this article, we will discuss the warm forming of AA7021 and AA7046.

## 1.4 Tensile test of aluminum alloy

Tensile testing, one of the most common mechanical testing techniques, is a destructive engineering and materials science test in which a controlled tension is applied to a sample until it completely fails. It is used to find out how strong a material is and how much it can be stretched before it breaks. The results of tensile tests are used in selecting materials for engineering applications. Tensile properties frequently are included in material specifications to ensure quality. Tensile properties often are measured during development of new materials and processes, so that different materials and processes can be compared. Finally, tensile properties often are used to predict the behavior of a material under forms of loading other than uniaxial tension [13]. The following figure shows a standard sample specimen.




It is a common practice to use tensile specimens to study the properties of aluminum alloys.

For example, Sung-Hwan Choia et al. investigated the deformation behavior of new Al-1%Mg-1.1%Si-0.8%CoNi heat resistant aluminum alloy by high temperature tensile experiments [14]. Elanghovan Natesan et al. investigated the monotonic and cyclic deformation behavior of A356 -T7 Cast Aluminum Alloys at different temperatures to obtain data related to their strength and ductility [15]. Dyi-Cheng Chen et al. used the results of tensile experiments to analyze their effect on capricious fracture [16]. Emad Scharifi et al. studied the deformation behavior of new Al-1%Mg-1%Si-0.8%CoNi heat resistant aluminium alloy by implementing dynamic tensile experiments at different strain rates to further analyze the mechanical properties of AA6082 and AA7075 [17].

# 2. WARM FORMING PROCESS OF ALUMINUM ALLOYS

## 2.1 What is warm forming?

Different forming techniques for aluminum alloys will produce different microstructures and mechanical properties. Nowadays, the commonly used forming techniques are: cold forming; warm forming; and hot forming. The recrystallization temperature is an important critical point. Under the action of heat and force, new crystals begin to form when metal atoms reach a certain high energy level, which is called recrystallization. Plastic deformation of metals below the recrystallization temperature is called cold working, and it is usually carried out at room temperature; plastic deformation of metals above the recrystallization temperature is called hot working. Warm working, (or warm forming), is a metal forming process carried out above the temperature range of cold working, but below the recrystallization temperature of the metal, normally is between 0.3 times the melting temperature of the metal and the recrystallization temperature of the metal. Warm forming can be performed under isothermal or non-isothermal conditions: forming means heating the blank and the mold at the same time, and the temperature of the sheet remains the same during the forming process, and no heat transfer occurs between the sheet and the mold; non-isothermal forming means that the sheet is only heated to a specified temperature before forming, and then formed in a mold at room temperature. The choice of isothermal or non-isothermal warm forming depends on the desired increase in formability [18].

Warm working may be preferred over cold forming because it will reduce the force required to perform the operation. Also, the amount of annealing of the material that may have been necessary for the cold formed part may be less for warm working.

Warm processing is performed to combine the advantages of both hot and cold processing [19].

Compared to cold forming, warm forming has several advantages. These include.

Less load on tools and equipment;

Greater metal ductility;

Fewer annealing operations (due to less strain hardening).

Compared to warm forming, warm forming offers the following advantages.

Less thermal energy requirements;

Higher component accuracy;
Better dimensional control;
Better surface finish;
Less thermal fatigue on the tooling, so the tooling lasts longer.

## 2.2 Warm forming application in the aluminum alloy

As we know, aluminum alloy has poor forming performance at room temperature, small total elongation, and the elasticity coefficient is only 1/3 of that of steel plate, which makes the metal flow difficult during forming, thus its application is limited to some extent, and steel is still the most widely used material in the automotive field. After research, it is found and proved that aluminum alloy has good plasticity, low deformation resistance and low forming difficulty at high temperature, so the warm stamping and forming technology of aluminum alloy has received wide attention, homogeneous thermal tensile tests at different temperature settings can observe and verify some mechanical properties of interest to us, such as stress-strain curves, yield strength, etc. We will also use this method in this thesis study.
As early as 1946, FINCH et al. conducted a study on warm forming of aluminum alloy sheets, and the results showed that the tensile properties were significantly improved when forming in the warm state. In the 1970s, it was discovered that aluminum alloys with a magnesium content of 6% could produce 300% total elongation at approximately 250°C [38]. So, in warm forming of aluminum, the mold and press bar are usually heated to a temperature range of 200 to 300°C. Later in 1978, a paper by F. Shehata et al. reported the finding: commercial aluminum alloys undergo a corresponding change in strain of 0 to 6.6% at temperatures between 20 and 300°C, that is, the higher the temperature, the greater the elongation [20]. In subsequent studies it was also found that the yield strength and tensile strength of the material decreased with the increase in temperature. Nowadays, it has become the basic principle of warm forming technology to improve the elongation property and plasticity of aluminum alloy by increasing its temperature during forming.
Among the aluminum alloys targeted for automotive use, the 5xxx and 6xxx series of aluminum were well studied and observed, the formability of the 5xxx and 6xxx series was significantly improved when warm forming was used. For example, Daoming Li and Amit Ghosh of the University of Michigan studied the tensile tests

of these two series over a range of warm forming temperatures and experimentally showed that the yield stress increased with increasing temperature and decreased with increasing strain rate [21]. Warm forming has not yet been applied in automotive parts production. However, since it can be carried out using a standard cold press, the investment required to implement it will not be very large [22].
As mentioned earlier, for certain critical parts of the body requiring higher strength, research on 7XXX series will be essential, which currently has limited applications in the automotive industry due to its high price and poor formability at room temperature. Nanjing University of Aeronautics and Astronautics and Ford Motor Company cooperated to study the warm forming of high strength 7xxx series (7075), and the results showed that the deep drawing and tensile formability of AA7075 could be improved significantly when the billet was heated to 140-220°C. When the temperature exceeds 260°C, the formability and post-forming mechanical properties start to decrease due to the effect of heating and forming process on the tempering of the material [23].
This figure below shows a warm forming method for a vehicle body, using the super strength material 7xxx aluminum alloy. The dissolution of $\eta'$ precipitations and dynamic recovery process at elevated temperatures lead to an increased formability. [24]

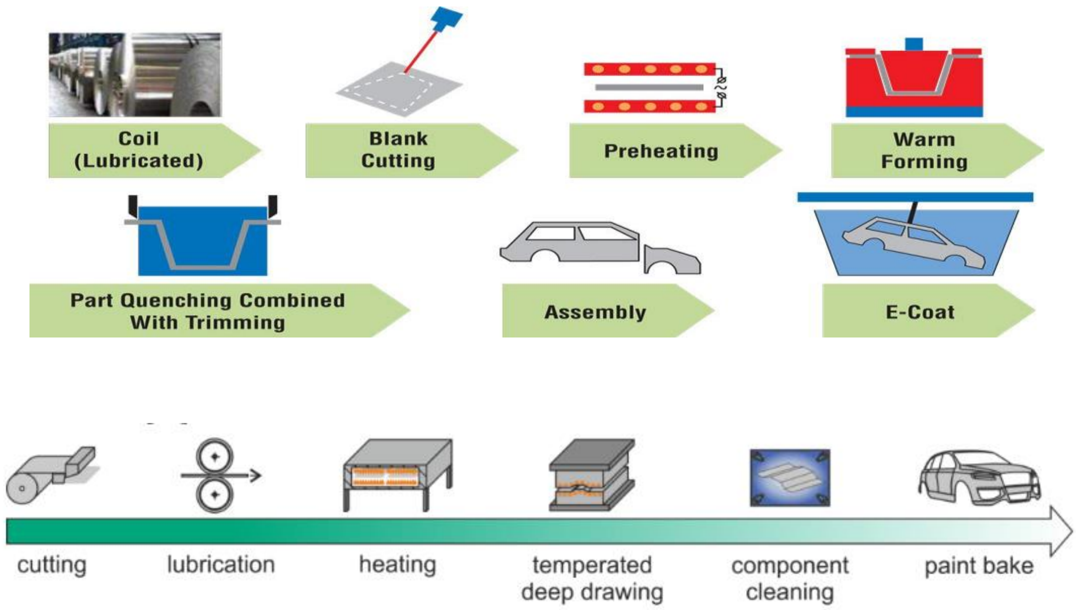



Figure 8: Warm forming method for vehicle body

### 2.3 Process route to form the aluminum alloys in warm forming

Warm forming is a very complex process and developing a robust, productive and economical manufacturing process is critical for aluminum alloys. It must be emphasized that: dimensional tolerances and characteristics, forming temperature, interface conditions (lubricant/friction and heat transfer), tool temperature, forming speed (or strain rate), insulation, heaters, temperature sensors, and incoming forming equipment all have a significant impact on the shape and characteristics of the final product and the economics of the process.

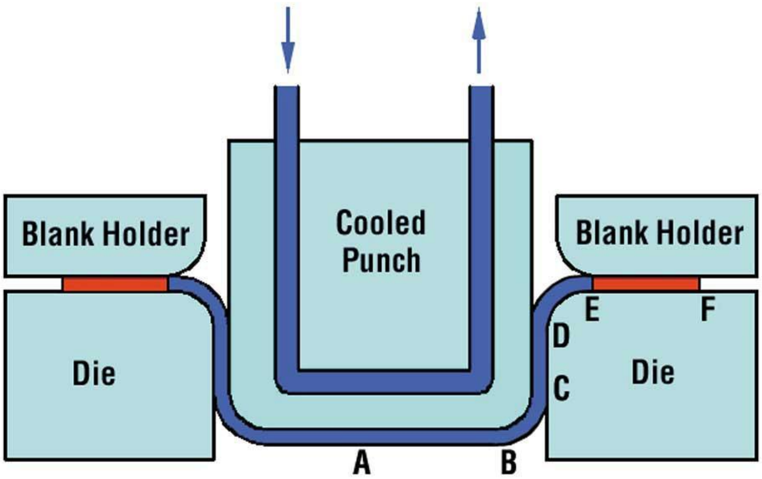



Figure 9: One classical non-isothermal forming

Warm forming is a deep drawing method that uses a die and a blank holder, heated to a certain temperature by a heater or other means, and a punch that is kept at room temperature by water cooling or other means, as shown in the figure 9, is a classical non-isothermal forming, which divides the hot-drawn aluminum sheet into five zones (AB, BC, CD, DE and EF) to illustrate the heating and cooling zones of the material. The blank is not heated beforehand and is clamped and deep-drawn by the die and the blank holder. The part between the blank holder and the die (E-F) is heated to reduce the compressive stress in the flange area. As the sheet enters the corner of the die (E-D), the punch wall (D-C) and the corner area (C-B) are cooled to increase strength and prevent premature sheet breakage. [18]

The heating elements, insulators, temperature sensors and temperature control devices mentioned above are part of the mold used for warm forming. There are many methods used to heat sheets and tools before and during the molding operation, depending on the production volume, type of molding process and equipment. Among the methods available for heating the tooling, resistance heating using a cartridge heater (as shown in figure 10) appears to be the most suitable for deep stamping.

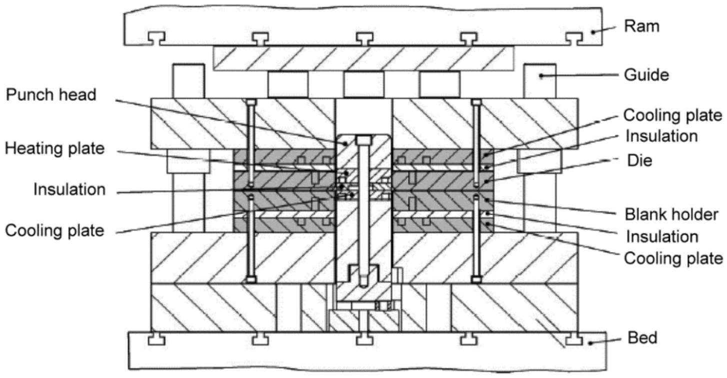



Figure 10: Heating system of forming, source from [18]

In addition, the press temperature has an effect on formability: as the press temperature decreases, formability increases. The effect of punching temperature on the ultimate stretch rate is shown in Fig 11.

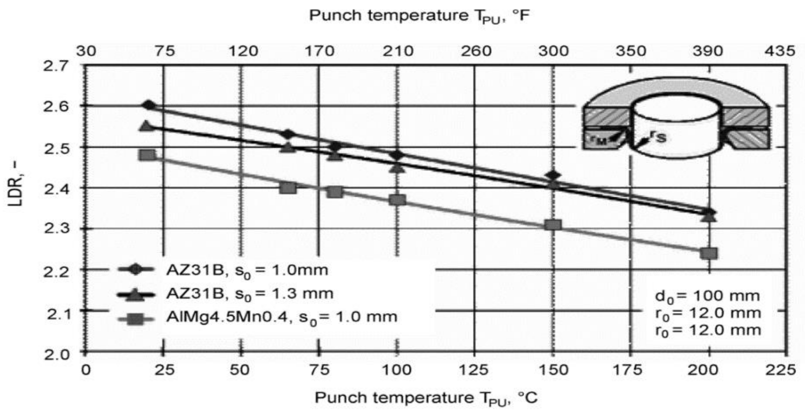



Figure 11: The effect of punching temperature on the ultimate stretch rate, source from [18]

In 2012, Imperial College London and other schools jointly used standard experimental techniques to determine the FLCs of aluminum alloys at high temperatures. the experiments showed that: 1. formability increases with increasing temperature; 2. the forming limit increases with decreasing forming speed; and 3. formability increases with decreasing strain rate. Therefore, in warm forming, the best ductility occurs at low speed, and the effect of decreasing the speed is similar to that of increasing the temperature. The following two pictures in fig 12 are the results obtained from the experiment.

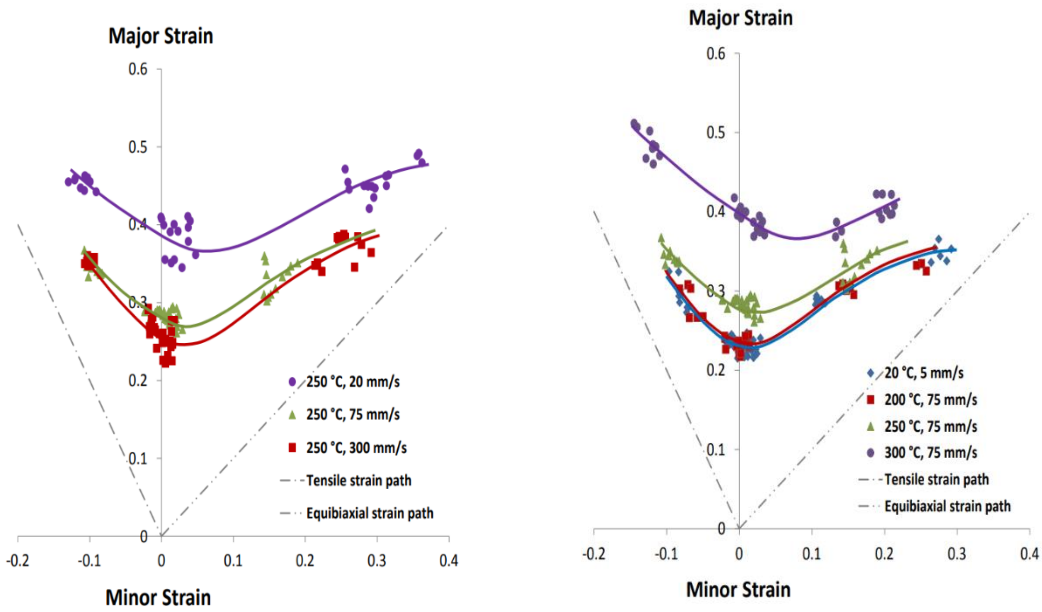



Figure 12: The relationship between molding speed and formability (left); The relationship between molding speed/temperature and formability (right)

However, warm forming technology is not perfect and has some limitations, such as:

1. Warm forming is being extensively studied in a laboratory environment, and there are no well-known press shops implementing this process.
2. Warm forming is still considered unsuitable for high-strength heat-treated aluminum alloys because the heating may affect the microstructure of the alloy, resulting in a decrease in strength after forming. This is the focus of future research.
3. Increased interfacial friction leads to the need for high-temperature lubricants.

The lubricant is one of the factors affecting the heat transfer at the tool, blank interface. Lubrication is more important in warm forming than in room temperature molding because the temperature changes the properties of the lubricant and it increases the tendency to occlude. With a dedicated lubricant, existing cleaning and degreasing processes can be utilized, so the investment required to implement warm forming in the manufacturing sector can be significantly reduced. Various lubricants for the process need to be evaluated and satisfactory lubricants must meet the following criteria.

a. Stability at operating temperature (no smoke or fumes)
b. Good lubricity to reduce friction
c. Hazard-free
d. Good adhesion properties
e. Low cost
f. Easy to apply
g. Easy to remove
h. Environmentally friendly

Nippon Steel Corporation, Nippon Quaker Chemical Corporation and Furukawa-Sky Aluminum Corporation have jointly developed a lubricant specifically for warm forming that meets several of the above requirements. The lubricant contains fatty acid esters, synthetic hydrocarbons, antioxidants, phosphate esters and emulsifiers. It has a flash point of 262°C and a dynamic viscosity of 35 mm2/s (at 40°C). Using this new lubricant, a warm forming test was performed on an AA5182 square shell with a cross section of 78 mm2 held by water cooling. The punch had a cross section of 78 mm2 and was water cooled at 25 °C. The temperature of the die and blank holder was kept at room temperature in cold forming and at 200 °C in warm forming. The degreasing ability of the lubricant was evaluated and later, during visual inspection, it was found that the wetted area covered more than 90% of the surface area. Thus, it can be proved that the new lubricant was judged to have good degreasing ability. The use of this new lubricant for warm forming has proven to be practical. However, since degreasing conditions vary depending on the automotive production line, putting warm forming into practical use still requires adjusting the lubricant performance or developing a new lubricant suitable for the production line [22].

## 2.4 Some practical warm forming applications

In this section, the solutions and practical applications of warm forming proposed by some companies and research institutes will be briefly introduced.
The basis for selecting any material to produce a part should be that the part will provide the best compromise between cost and function. Therefor in some studies, the first consideration is to solve the technical bottleneck in warm forming, and the second consideration is to reduce the cost of warm forming. These goals can be achieved by reducing the forming load (and therefore the press capacity requirements), reducing wear, etc.

**Warm hydroforming:**
Warm hydroforming is an innovative forming technology in which sheet or tube material is formed by pressurized fluid at warm forming temperatures. Warm hydroforming of aluminum alloys combines the advantages of warm forming and hydro-mechanical drawing. The process improves formability and results in a more uniform thickness distribution of the formed part [25]. However, it is difficult to obtain a uniform temperature in the mold. In addition, the cycle time is relatively long. Therefore, the process may only be economical for special applications and small production runs. There are two types of warm sheet hydroforming: if the tool used is a punch, it is named warm water mechanical deep drawing (WHDD), and if it is a mold, it is called warm water sheet hydroforming with mold (WSHF-D). Mevlüt Türköz et al. conducted an experimental study of this technology in 2017 and concluded that the WHDD process is better for forming in manufacturing cups conclusion. However, since defect-free parts can be manufactured using WSHF-D and the WHDD process is quite complex, there would be no mistake in choosing WSHF-D to simplify the process [26] [27].

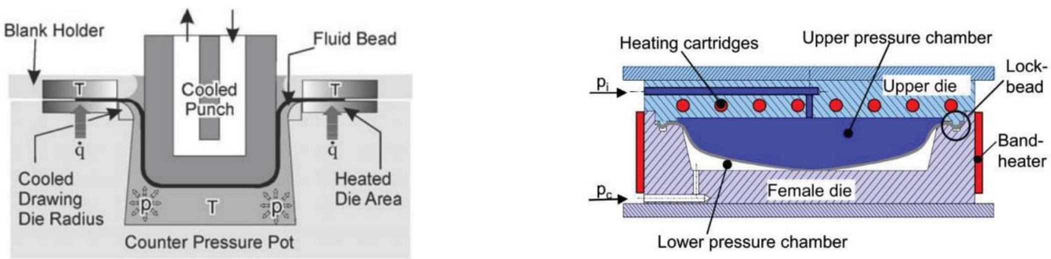



Figure 13: Sketch of warm water forming

**Preforming, Annealing, and Finish Forming:**

It is also a recently investigated warm forming process to form AA5182 and AA5754 automotive panels. There are three specific steps:

1. Preforming, where the part is partially drawn as deep as possible without necking or splitting;
2. Annealing at approximately 350°C to remove cold working stresses; and
3. Drawing the blank into its final shape.

The first and third of these steps are performed at room temperature. The intermediate annealing heat treatment eliminates the cold work accumulated in the material during the first drawing. This process is capable of forming more complex parts than conventional aluminum stamping processes. However, this process is not likely to be able to fully anneal the sheet and does not achieve the original hardness of the incoming material. While the preform-annealing sequence allows for improved drawability, the costs associated with the additional processing steps make the process too costly [28] [29].

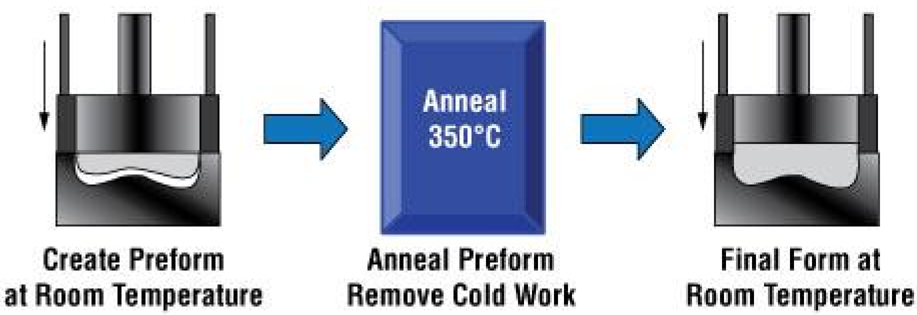



Figure 14: Brief view of the steps of preforming, annealing and finishing forming

**Quick Plastic Forming (QPF):**

QPF (Quick Plastic Forming) is a modification of SPF (isothermal Super Plastic Forming) due to cost considerations [30], which uses air or gas pressure to press a heated blank onto a heated mold surface, and has been successfully introduced as a forming technique of aluminum sheets in automotive industry in the last year [31]. QPF is responsible for high production volume, SPF is responsible for low production volume. The traditional curled metal shell mold in QFP, has limitations such as long process time and unstable quality. Therefore, Chin-Wei Liu et al. investigated and designed a demolding mechanism to improve the process efficiency and dimensional accuracy of QPF. The results of the study showed that their proposed mechanism can greatly reduce the process time, as it completely replaces most of the operations of specimen movement after molding [30]. Prior to 2008, General Motors used this method to claim some of their automotive parts. GM used the technology to make the entire outer panel of the Malibu Maxx's liftgate in one piece, instead of two. General Motors claims that the process they have developed and the cost-effective sheet material make blow-molded aluminum feasible in a growing number of vehicles and will ensure lighter, more fuel-efficient cars of the future.

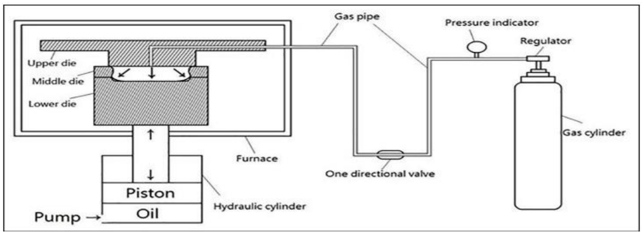



Figure 15：schema of Quick Plastic Forming (QPF)

# 3 EXPERIMENTAL PROCEDURE

## 3.1 Preparation of experimental

According to the research arrangement for the thesis, we decided to study and discuss three different aluminum alloys, they are: AA6016, AA7021 and AA7046, the number of samples prepared for these three alloys corresponds to: 6, 6 and (8 + 2) respectively, of these, 8 were used for tensile testing and 2 for metallographic studies. Some detailed information about the original samples is summarized in the following tables and pictures.

**Table 5 : material information**

| Alloy | Numbers | Thickness (mm) | Solubilized (°C) | Pre-aged (°C) |
|---|---|---|---|---|
| **AA6016** | 6 | 1.3 | 540 | At 100 °C 20 min |
| **AA7021** | 6 | 3.8 | 515 | NO |
| **AA7046** | 8 + 2 | 1.3 | 480 | NO |

Furthermore, for the same alloys: Sheet metal strips about 30 x 300 mm and the residues of the cut. Figure 15 shows the standard plan view of the sample.

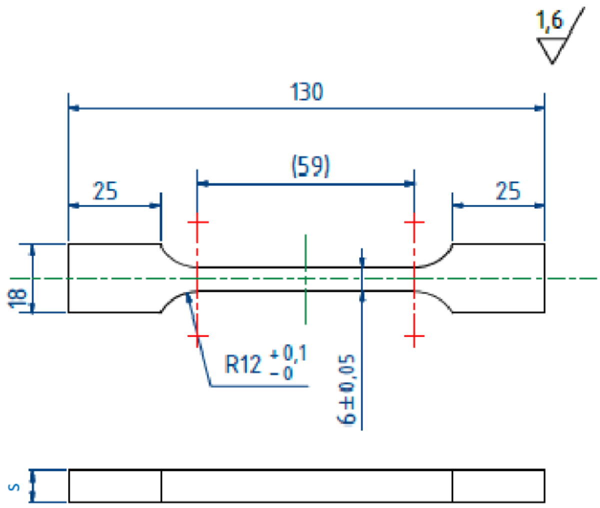



Figure 16： standard plan view of sample

Among them, **AA6021** as the representative of 6000 series aluminum alloy has been widely used in the automotive industry. 6000 series aluminum alloy (Al-Mg-Si) is mainly used in the outer plate of automobiles and plays an important role in the light weighting, but due to the low strength, it is difficult to achieve the light weighting of the side impact beam and B-pillar and other load-bearing structural parts of automobiles. Therefore, more and more eyes and research topics are turning to 7000 series aluminum alloys, and the development of medium-strength 7000 series aluminum alloy sheet is still in the initial stage. **AA7021** and **AA7046** were selected as samples. The composition of these three aluminum alloys is listed in the following three tables.

Table 6 AA6016

| Alloy | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| **AA6016** | 1.2% | 0.5% | 0.2% | 0.2% | 0.6% | 0.1% | 0.2% | 0.15% |

Table 7 AA7021 and AA7046

| Alloy | Mg | Zn | Zr | Cr | Si | Mn | Cu | Ti |
|---|---|---|---|---|---|---|---|---|
| **AA7012** | 1.66% | 5.14% | 0.09% | 0.04% | 0.16% | 0.05% | 0.15% | 0.05% |
| **AA7046** | 1.5% | 6.5% | 0.1% | 0.05% | 0.1% | 0.05% | 0.1% | 0.05% |

By the way, the values shown in the tables above are standardized averages and are not data tests performed specifically for this experimental sample.

## 3.2 The heat treatment process

As we show in Table 5 about the information of sample, AA6016 has undergone a complete heat treatment process, including solubilized at 540 degrees Celsius and pre-aged at 100 degrees Celsius for 20 minutes. Therefore, we will heat treat two sets of samples of AA7000, especially AA7046.

### *3.2.1 The heat treatment of AA7000 series*

Heat treatment of aluminum differs significantly from steel in that it is a process by which the strength and hardness of a specific subset of aluminum alloys (including the 2XXX, 6XXX, 7XXX and 8XXX series) is improved, i.e. precipitation hardened forged and cast alloys. In addition, annealing may be required for parts that have undergone strain hardening during the forming process. Typical aluminum heat treatments are.

a. Preheating or homogenization to reduce chemical segregation in the cast structure and improve its machinability
b. Annealing, softening after strain hardening (work hardening) and heat treatment of alloy structures to reduce stress, stabilize performance and dimensions
c. Solution heat treatment to achieve solid solution of alloy composition and

improve mechanical properties

d. Precipitation heat treatment to provide hardening by precipitation of components from solid solution

Depending on the specific process used, furnace temperatures can range from 115 to 537°C. Age-hardenable 7xxx series aluminum alloys for high-performance structural applications are typically processed in the form of plates, extrusions or forgings. For thick plate products, a typical processing schedule involves casting, homogenising, hot rolling, solution treating, quenching, stress relieving by stretching and age hardening [32]. as shown Fig.

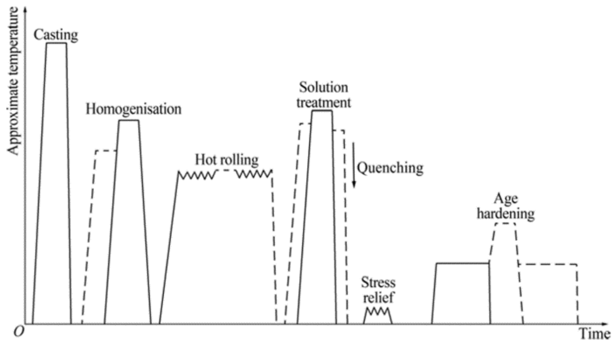



Figure 17: heat treatment process

### *3.2.2 The handling of AA7021*

After the discussion, we decided to divide the six AA7021 samples into two groups of three samples. 3 samples of the first group was kept without any pre-aged procedure and other 3 of the second group was pre aged at 100°C for 20 minutes. The structural changes that occur at high temperatures are fundamentally different from those that occur at room temperature. By reheating the quenched material to 100°C and allowing the alloy to change state from T4 to T6, the effects of precipitation on mechanical properties are greatly accelerated and often exacerbated. It has been shown that a characteristic of the effect of high temperature pre-aged on tensile properties is that the increase in yield strength is more pronounced than the increase in tensile strength. Ductility, as measured by elongation, also decreases. Thus, alloys in the T6 condition have higher strength but lower ductility than the same alloys in the T4 condition. In the laboratory, we placed three AA7021 samples into a pre-set temperature (100°C) oven, and after 20 minutes, it was removed and water-cooled.

### *3.2.3 The handling of AA7046*

As shown in Table 5, a total of 10 AA7046 samples, 8 will be used for tensile testing and two for metallographic studies, but in any case, these ten samples will be first subjected together to the same procedure, i.e., two hours of solubilization at 480°C. Solubilization is the first step of heat treatment and consists is a heating process at very high temperatures, up to max. 575°C, but 480°C for our choice, followed by a cooling. The solution annealing treatment was carried out in an IONOS 501 muffle furnace located in the laboratories of the Politecnico di Torino, with cooling by water quenching, and 10 samples were subjected to this step simultaneously.

In conjunction with the scheduling of later tensile experiments, 5 of the eight AA7046 samples were artificially aged, with the same parameters chosen as for AA7021 and AA6016, both at 100°C for 20 minutes.

Finally, I have summarised the heat treatment procedure in the form of a table (table 8) :

**Table 8 Heat treatment information**

<table>
<tr><th>Aluminum alloy</th><th>Thickness</th><th>Solubilized</th><th>Numbers</th><th>Pre aged</th></tr>
<tr><td>AA6016</td><td>1,3 mm</td><td>At 540°C</td><td>6</td><td>Yes at 100°C, 20min</td></tr>
<tr><td rowspan="2">AA7021</td><td rowspan="2">3,8 mm</td><td rowspan="2">At 515°C</td><td>3</td><td>No</td></tr>
<tr><td>3</td><td>Yes at 100°C, 20min</td></tr>
<tr><td rowspan="3">AA7046</td><td rowspan="3">1,3 mm</td><td rowspan="3">At 480°C</td><td>2</td><td rowspan="2">Yes at 100°C 20min</td></tr>
<tr><td>3</td></tr>
<tr><td>3</td><td>No</td></tr>
</table>

### 3.3 The metallography study of AA7046

The examination of the microstructure is one of the main means of evaluating alloys and products, and is one of the key tools for determining the phase diagram to determine the effects of various manufacturing and heat treatments, and to analyze the causes of failure. The main microstructural changes occur during freezing, homogenization, hot or cold working, annealing, etc. Microstructural examination is usually used to investigate the number of phases (single or multiphase) and the type of invariant reactions (eutectic or peritectic, or other). In particular, the characteristics of each phase, such as composition, size, shape, distribution, color, orientation and hardness, can be examined. Metallographic analysis is performed on the assumption that the observed microstructure represents the true structure of the sample. This tool has been successfully used to determine multi-component phase diagrams since the 1920s. According to the research focus of this thesis, we decided to perform experimental metallographic analysis of AA7046, with high-temperature pre-aged and non-high-temperature pre-aged tests and optical microscopy observations, respectively.

Afterwards, we cut the two samples after the heat treatment under the guidance of the professor

All experimental steps were done in the laboratory of Politecnico di Torino.

- Cutting
- Mounting
- Grinding
- Polishing
- Etching
- Optical microscope

#### 3.3.1 The step of test

As we mentioned before, 10 (8+2) AA7046 samples were simultaneously solubilized and quenched (water-cooled), 2 of the 10 samples were prepared specifically for metallographic studies, and we will perform high-temperature pre-aged (at 200°C for 20 min) for one of them, while leaving the another untreated. Afterwards, we cut the two samples under the guidance of the professor, and the **cutting** was done by the TR80 EVOLUTION Abrasive Cutter.

Figure 17: Metallographic cut-off machine.

After the sample is cut, it must be mounted. The sample is fixed in a suitable inlay material that retains sharp edges and will wear off at the same rate as the sample in future preparation steps. The two main techniques used are hot compression mounting and cold mounting. Both methods have their advantages and disadvantages depending on the type of sample and the number of samples required. Cold mounting (room temperature) is often used for epoxy mounted samples by simply mixing and pouring the epoxy onto a sample placed face down on the cold mounting ring. Cold **mounting** has to be preferred to the hot one if the alloy is sensitive to microstructural modifications (precipitation) also at low temperature (around 100°C). Once the epoxy has cured, it is time to prepare the specimen. Due to the relatively poor adhesion between the specimen edge and the epoxy plug, care must be taken when cold mounting; gaps often form, which can degrade the quality of the specimen.

In this case, we use the Technovit 4071 powder and solution (it is a cold packed resin), which can be quickly mixed and solidified at room temperature in a 2:1 ratio. First of all, carefully placed into at the middle of bottom of small mold, then we pour the resin solution that we mentioned above into the mold and leave it to cure before removing them.

Figure 18: Embedded samples

To obtain a flat and uniform surface as well as to eliminate tool scratches on the sample due to cutting, we have to do the step of **grinding**, the grinding was performed on a Remet LS2 polishing machine, grinding is performed with sandpaper (paper discs with particles of abrasive material attached). Each of the abrasive paper has a number that corresponds to the size of the hole in the sieve used to select the abrasive. The larger this number, the smaller the size of the abrasive. The most commonly used papers in metallographic preparation range from 80 to 4000. Special emphasis should be placed on:

**a**. I must rotate the sample 90 degrees each time I change the sandpaper;

**b**. During the grinding process, make sure there is water flow and the right amount of lubricating fluid;

**c**. The sample must be thoroughly cleaned before proceeding from one grinding stage to the next.

This way we can get scratches that are uniform in size and parallel to each other, indicating a relatively successful grinding.

The next step is **polishing**, the purpose of polishing is to achieve a scratch free surface to be viewed under the metallographic. Both samples were polished on grinding wheel by using the finer diamond abrasive (1 micron and 3 micron), and the lubricant is necessary during the process. After each polishing, the specimen was washed with water and alcohol and then dried with paper or electrical dryer, and check it by normal Microscope.

The last step of the preparation is **etching**, "Microscopic examination of properly polished, unetched specimens will only reveal structural features such as inclusions and cracks or other physical defects. Etching is used to highlight, and sometimes identify, microstructural features or phases that are present. Even in carefully prepared specimens, disturbed metal surface layers resulting from the final polishing stage are always present and must be removed. The etchant is usually a dilute acid or dilute base in water, alcohol or some other solvent. When an acid or base is placed on the surface of a specimen, etching occurs due to the different rates of attack of the various phases present and their orientation. The etching process is usually accomplished by applying an appropriate solution to the specimen surface for a few seconds to a few minutes [33].

For this test, this step is done for 60 seconds in order to show the microstructure by using Keller's reagent, consisting of:

- 95 % water;
- 2.5 % nitric acid, $HNO3$;
- 1.5 % hydrochloric acid, HCl.
- 1 % hydrofluoric acid, HF.

Before etching, we have to clean the surface, inside the small beaker the polishing face is forward up, and use the tongs is better. After etching, we have to wash it with running water, and the it was rinsed with alcohol, the drying process must be performed without direct contact with other materials, so we dry it with warm air to prevent traces of the acid from remaining on the surface.

### 3.3.2 Observation of the microstructure

After etching and drying, we can first observe the microstructure under a general microscope to ensure that our previous process was correct and to get a general idea of the microstructure (e.g., whether a second phase can be observed), after which the sample can be observed with an optical microscope.

Optical microscopy (OM) is a classical technique for phase identification. Optical examination of the sample is of great value because many phases can be easily distinguished in OM. A simple examination of the sample from low to high magnification can reveal approximate volume fractions, microstructure types, homogeneity, and potential surface contamination such as oxidation. the contrast mechanism of OM is complex and it is easier to distinguish certain phases in OM than in electron microscopy. the main limitations of OM include (1) limited magnification (typically ≤ 2000x) that prevents it from being used to

observe potentially fine microstructural features. (2) There is essentially no information about the composition and crystal structure of the phases [18]. Many early phase diagrams were determined using OM alone.
In this paper, we used a Reichert-Jung optical microscope (an inverted optical microscope) located in the laboratory of the Politecnico di Torino for manipulation and observation.
In this inverted light microscope, the specimen is placed on the viewing plane with the viewing surface facing down. Using a knob system on the light microscope, the focus, brightness, contrast and magnification of the image can be adjusted. Depending on the needs of the paper, I observed and recorded the surface images at 5,10,20,50 and 100x magnification.

Because the optical microscope observation of the first etching was not enough to prove the microstructure, in fact, it was difficult to identify the grain boundaries after the first etching, so we decided to perform a second etching, and the figure below shows the optical microscope observation after the second etching, which proved that the grain boundaries could be observed after the second etching.

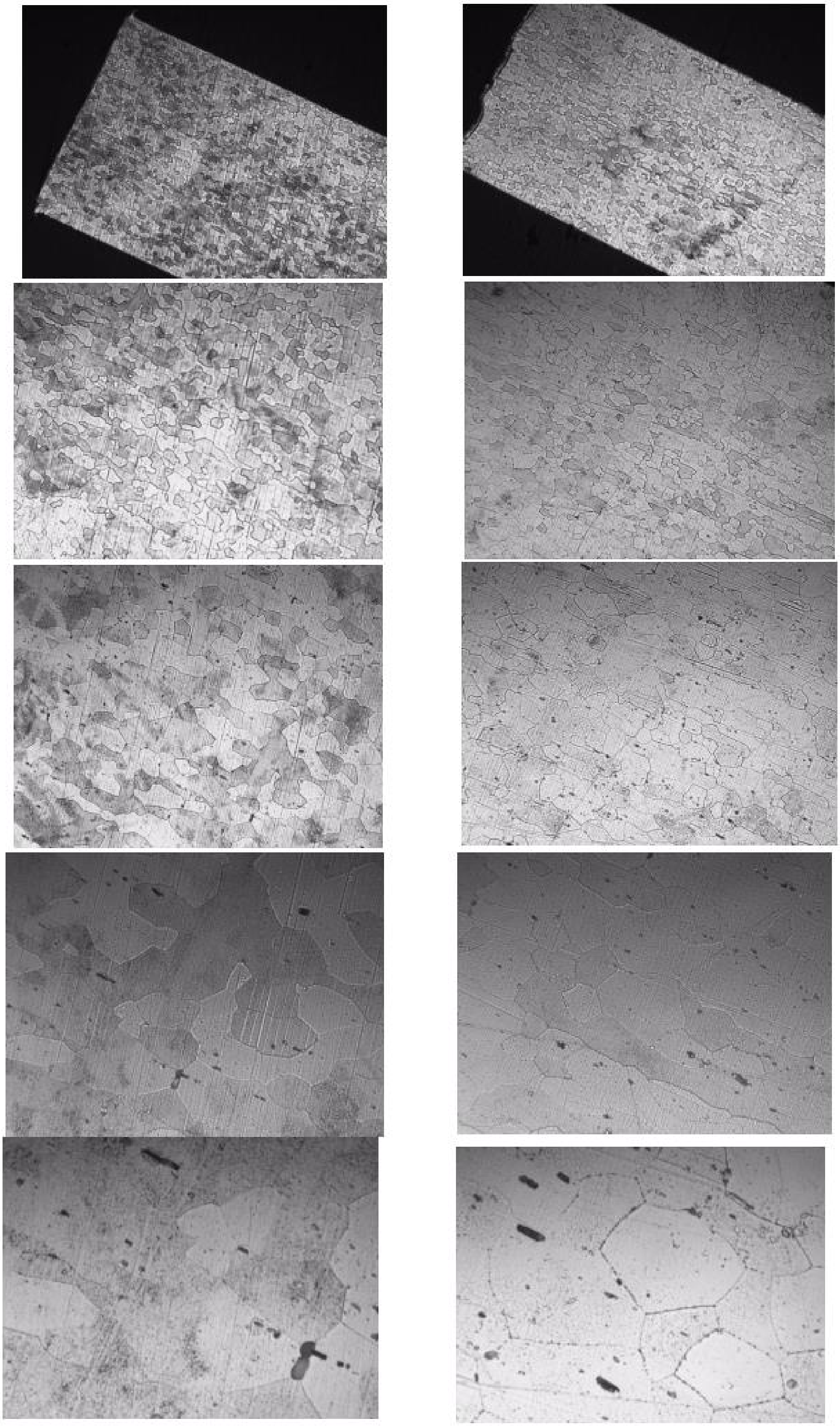


Figure 19: Metallographic images of 2nd etched; From top to bottom is magnified 5,10,20,50 and 100 times, the left is the one heat treatment, the right is one as received.

### 3.3.3 Microstructure analysis

Due to the soft metallic nature of aluminum alloys, the elimination of all scratches is not a simple process and must require careful handling, especially during the polishing phase, to eliminate the smallest scratches on the surface. As pointed out earlier, we carried out two etchings and the time of moment is one of the most important parameters in the metallographic analysis process: too short a time and the grain boundaries may not be clearly observed; too long and the surface color is too dark and unobservable. We may get a better view by performing two etchings.

As can be seen in the two sets of images above, the aluminum matrix is roughly homogeneous, the grain boundaries are well defined in both sets and we also observe precipitates (smaller black dots) which can be interpreted as the appearance of a second phase, which can be found as pores in the matrix under a high magnification lens.

Under Optical Microscopy, the metallography of the two sets of mounted specimens can be considered essentially approximately the same, although they exhibit some differences. Given this effect, we did not proceed with additional OM analysis because we did not believe it was possible to distinguish submicron precipitates in different specimens by OM.

## 3.4 The tensile test

The tensile test is the simplest and most direct way for us to analyse the mechanical properties of a material. In order to verify the effect of warm forming on the material, the following tensile tests were carried out. The purpose of this study was to verify the applicability of the Wen warm forming process in the automotive industry. in thesis of  Wang Minye in 2015 [34]， a full-scale tensile study was done on AA6016 and AA7046 under high temperature conditions, this time, we will do some different set-ups, such as partial tensile tests on some samples and full tensile tests on some samples, in order to try to study the warm forming process in a more detailed way. The requirements and parameters for each sample are detailed in the table 9. Notice that the set temperature for the tensile test was set above 200°C for the 6000 series aluminum alloys, but below 200°C (175°C) for two different sets of 7000 series alloys. This is because the previous tests concluded that the mechanical properties of the examined 7xxx alloys are not much affected by the (simulated) warm forming up to about 200°C, therefore, this test will focus on examining the effect of warm forming below 200°C on 7000 series [38].

**Table 9 The parameter of tensile test**

| Aluminum alloy | Num | Pre-Aged | WT tensile up to | Strain rate | RT tensile full test | Strain rate |
|---|---|---|---|---|---|---|
| AA6016 | 3 | Yes | 10% strain at 225°C | 10 mm/min | Yes | 10 mm/min |
| | 3 | | 10% strain at 200°C | | | |
| AA7021 | 3 | No | 10% strain at 175°C | | Yes | 10 mm/min |
| | 3 | Yes | | | | |
| AA7046 | 2 | Yes | Full test at 175°C | | No | |
| | 3 | No | 10% strain at 175°C | | Yes | 10 mm/min |
| | 3 | Yes | 10% strain at 175°C | | Yes | 10 mm/min |

### *3.4.1 The preparation of experiment*

The tensile tests were carried out in the laboratory located at the Politecnico di Torino. The machine used was an universal testing machine (Z050, shows in the figure 3) made by Zwick Roell.

Figure 20：the picture of tensile test machine

As can be observed from the table 9: for AA6016, we observe the effect of tensile on the material for the same strain rate but at different temperatures for aluminum alloys that have been pre-aged at high temperatures (100°C for 20 mins); for AA7021 and AA7046, we mainly observe the comparison between pre-aged and unaged (also say that pre-aged at room temperature) materials under the same strain rate and temperature treatment (175°C). According to the experimental requirements, all but two samples of AA7046 will be subjected to two separate tensile tests. The first part of the test is conducted at high temperatures (175°C, 200°C and 225°C, respectively) to simulate warm forming; the second part of the test is conducted at room temperature after the samples are air-cooled to room temperature to measure the mechanical performance of the formed parts.

When conducting the high temperature tensile test, three heating rods were used to touch the upper, middle and lower areas of the sample separately, to ensure uniform heating, after which the oven was closed around the test tube and began to heat up until the set temperature was reached. One problem we noticed was that due to thermal transients, the heating rate started to decrease as the temperature approached the set temperature in order to reach the thermal stabilization condition. Once the stability condition is reached, the deformation phase of the samples starts automatically. However, if we operate in this way, we will spend too much time in the final phase of the heating process and it also violates the prerequisites of uniform heating and therefore not compatible with those used to complete a production cycle in the automotive industry. Therefore, to avoid this, we first set a higher temperature, 50 degrees higher than the temperature we need, thus avoiding a lower heating rate in the final stage, and reducing the time and ensuring uniform heating. When the desired temperature was about to be reached, we manually operated the computer system to stop the heating and then changed the starting temperature back to the one we needed and the machine would automatically start the tensile test. Although we observe that the temperature will continue to increase due to thermal inertia and may exceed our desired temperature, but this increase is relatively small and within a manageable range, does not alter the results obtained.

### *3.4.2 The process of experiment*

The first step is to gently wipe the sample with alcohol to keep the sample and the experimental equipment clean. First place one end in the groove, and then adjust the height of the horizontal axis to fit the size of the sample, to ensure that the sample ends are exactly in the upper and lower groove, respectively, at this time should also pay attention to the display on the right column of the experimental equipment, the display shows the number of the force is best in 0 ~ 5 N. After making sure that the sample is perfectly fitted into the groove, install the fixing block, then bring the heating rod close to the sample, closed the heating oven, and then, place the laser device in the proper position. Transfer the eyes to the computer screen, enter the experimental parameters (width and thickness measured in advance with a ruler, temperature, pre-stress, speed), turn on the laser and start heating (see the tips in Section 2 for the heating procedure). If it goes well, the experiment will stop automatically when the strain reaches 10%, at which point the laser is turned off and the heating oven is carefully opened, allowing the sample to cool down in air-cooled conditions.

Once we have completed all the high-temperature tensile tests, we begin the room-temperature tensile tests with the exact same procedure, except that the heating process is eliminated. It is important to emphasize that we re-measured the width and thickness of all samples. Also, we could only perform the room temperature tensile test on samples that did not break during the high temperature tensile test, and this time, we stretched until the samples broke before stopping the test.

The following pictures are of all samples after the experiment (after breakage) The experimental system automatically saves the data for me. In this section, I organize and optimize the data saved by the system again and derive the actual stress-strain diagram. I will divide it into three subsections to talk about the stress-strain diagrams of AA6016, AA7021 and AA7046 respectively.


Figure 21: All samples after the experiment (after breakage)

First, extracting information from the system documentation that is useful to me.
1. cross-sectional area
2. the sample growth amount and the applied force at a given moment

With this information the stresses ($\sigma_0$) and strains ($\epsilon_0$) of the samples were calculated. However, the stresses $\sigma_0$ and strains $\epsilon_0$ in here are engineering values, and the following 2 equations are needed:

$$\sigma_{true} = \sigma_0 \times (1 + \epsilon_0) \qquad formula\ 1$$

$$\epsilon_{true} = \ln(1 + \epsilon_0) \qquad \qquad formula\ 2$$

to calculate the true stresses $\sigma_{ture}$ and strains $\epsilon_{ture}$ and to create a stress-strain diagram.

### *3.4.3 The result and the diagram of AA6016*

The figures and the table show the final result of AA6016:

**Table 10 AA6016 tensile test**

| Order | Temp. | Final strain | Rp0.2 | Full test | Fracture strain | Rp0.2 | UTS |
|---|---|---|---|---|---|---|---|
| **1** | | 10% | | Yes | 16,4% | 207 MPa | 296 MPa |
| **2** | 200°C | 8,7% | 110 MPa | No | | | |
| **3** | | 10% | | Yes | 18,7% | 206 MPa | 290 MPa |
| **1** | | 10% | 97 MPa | Yes | 16% | 209 MPa | 297 MPa |
| **2** | 225°C | 8,6% | 95 MPa | No | | | |
| **3** | | 10% | 105 MPa | Yes | 15,4% | 206 MPa | 288 MPa |

- Unfortunately, in each of these two sets of experiments, one sample broke at less than 10% strain during high temperature tensile (both 225°C and 220°C), meaning that 10% is too much for warm forming for this alloy at this temperature.

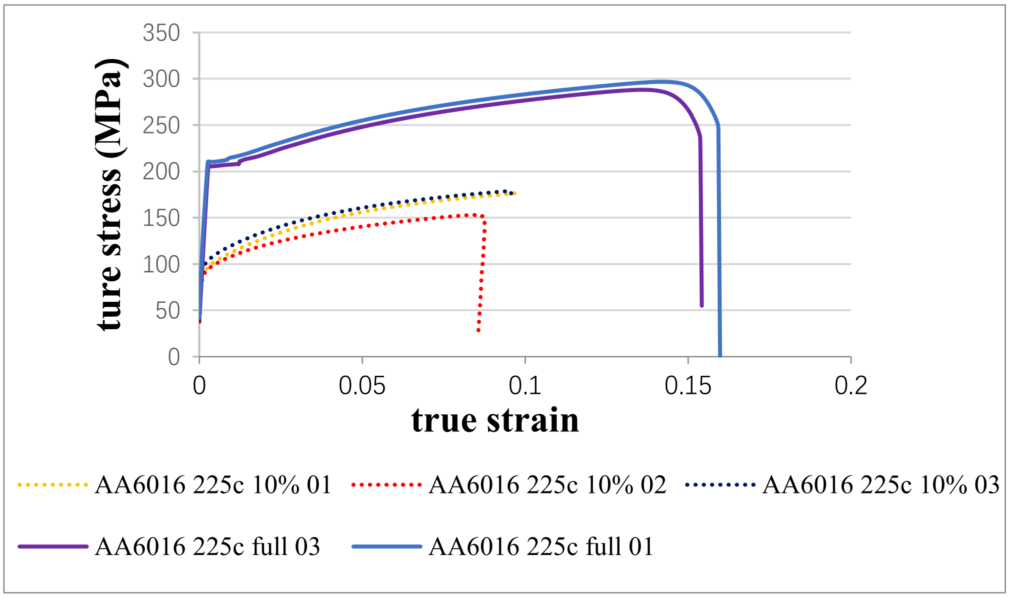



Figure 22：AA6016 225 °C up to 10% full test

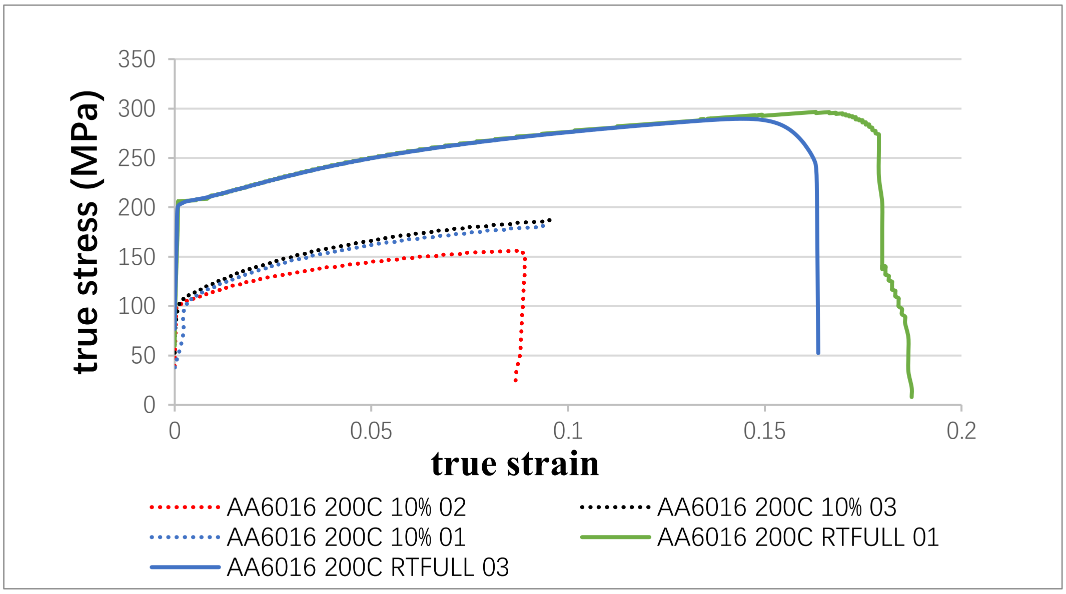



Figure 23: AA6016 200°C up to 10% full test

- The demonstrated yield strength rates in the 200°C tensile test is slightly higher than those in the tensile test at 225°C. However, secondary tensile tests after air cooling to room temperature for both sets of samples showed approximately the same yield strength, but at essentially twice the value demonstrated in the high temperature tensile tests;

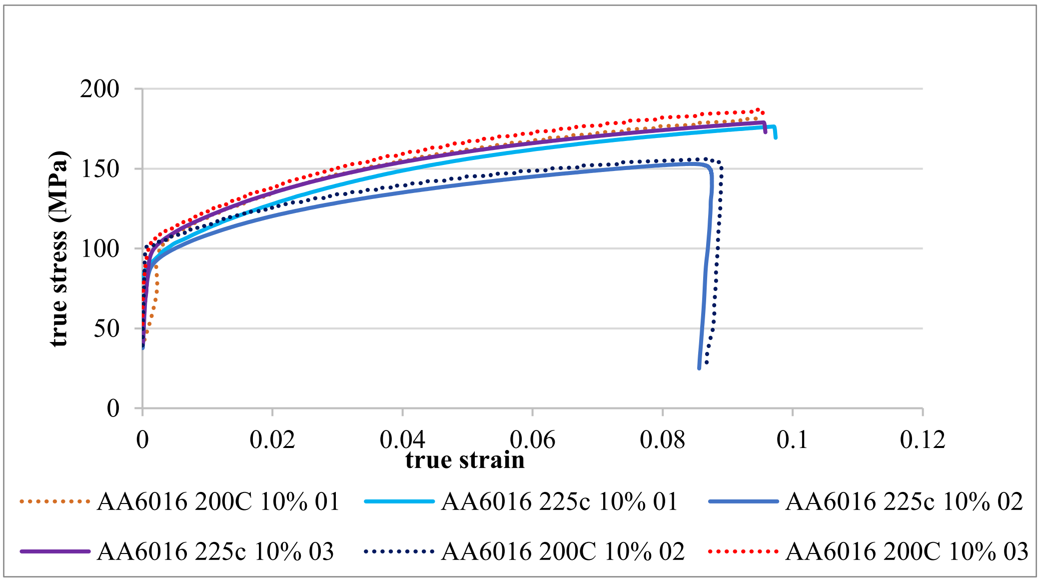



Figure 24: AA6016 in different temperature

- strains after room temperature tensile ranged from 16% to 20%;
- The UTS of the two sets of experiments also did not show much difference.

### 3.4.4 *The result and diagram of AA7021*

The figures and the table show the final result of AA7021: The aged in the images are labeled as pre-aged and not aged as not pre-aged.

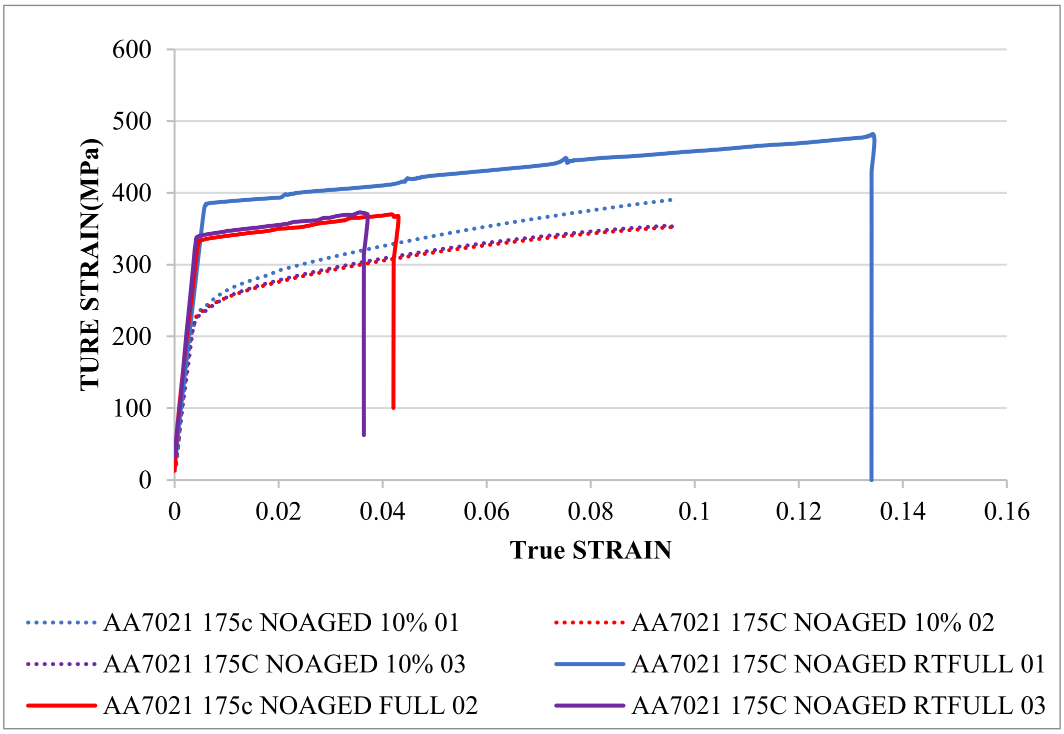



Figure 25：Comparison of tensile test in different pre-aged condition in

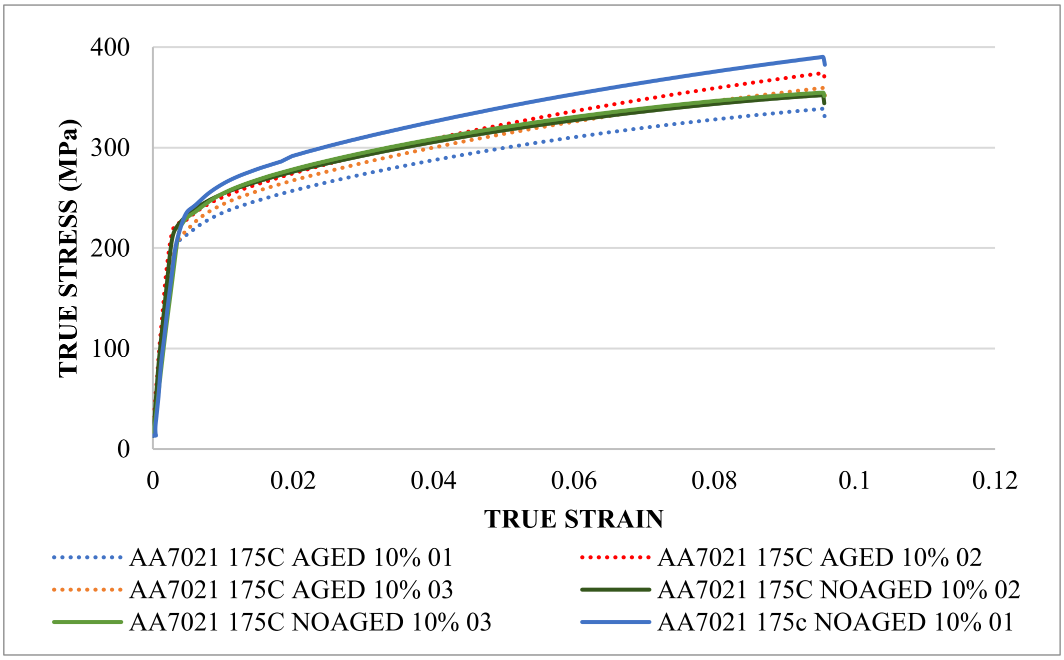



Figure 26：Comparison of warm tensile test and room temperature full tensile test of no pre-aged AA7021

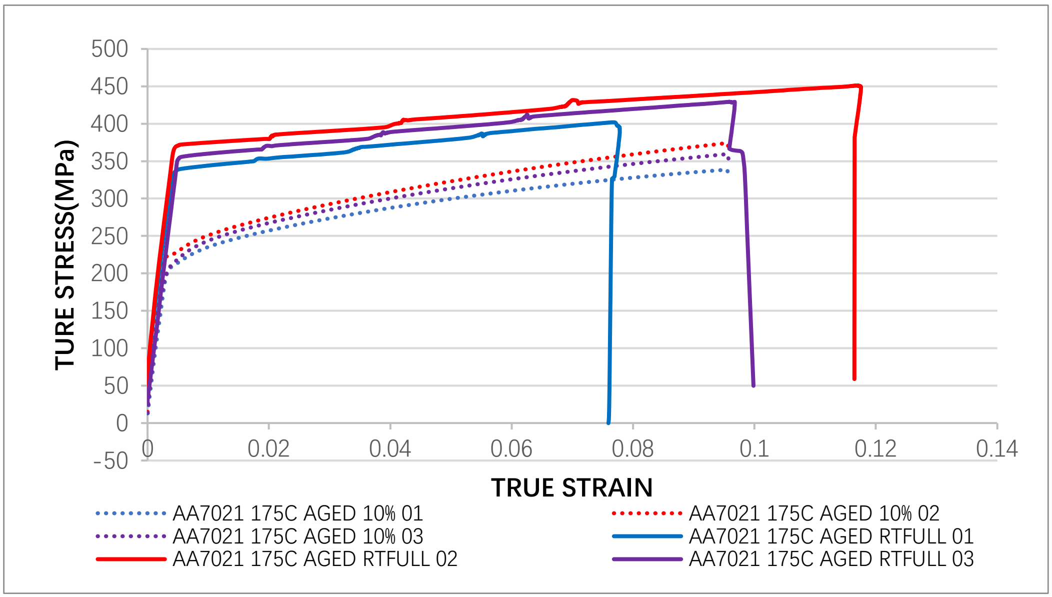



Figure 27: Comparison of warm tensile test and room temperature full tensile test of pre aged AA7021

| Order | Pre AGED | Final Strain | Rp0.2 | Full test | Fracture Strain | Rp0.2 | R |
|---|---|---|---|---|---|---|---|
| **1** | YES | 10% | 217 MPa | YES | 7,6% | 340 MPa | 401 MPa |
| **2** | | | 228 MPa | | 10% | 371 MPa | 451MPa |
| **3** | | | 218MPa | | 11,7% | 358 MPa | 427 MPa |
| **1** | NO | 10% | 236 MPa | | 13,4% | 386 MPa | 478 MPa |
| **2** | | | 232 MPa | | 4,2% | 337 MPa | 370 MPa |
| **3** | | | 233 MPa | | 3,7% | 341 MPa | 373 MPa |

**Table 11 the tensile test of AA7021**

- In the high temperature tensile test at 175°C, the yield strength of the room temperature aged alloy was slightly higher than that of the high temperature aged (100°C, 20 minutes) alloy.
- In Della Porta's paper [40], he concluded that the warm forming of AA7021 was best at 175 °C by conducting tensile experiments at different temperatures. In my experiment, the first half of the tensile experiment simulating warm forming yielded a higher RP0.2 than he did, but the second half of the mechanical verification experiment was not very successful and did not provide a better basis for his conclusion better evidence.
- After air cooling to room temperature, the two groups of alloys showed similar yield strengths in the second tensile test at room temperature.
- This test showed that both alloy samples broke too quickly in the second tensile test at room temperature, especially in the unaged group.

### 3.4.5 *The result and diagram of AA7046*

The figures and the table show the final result of AA7046:

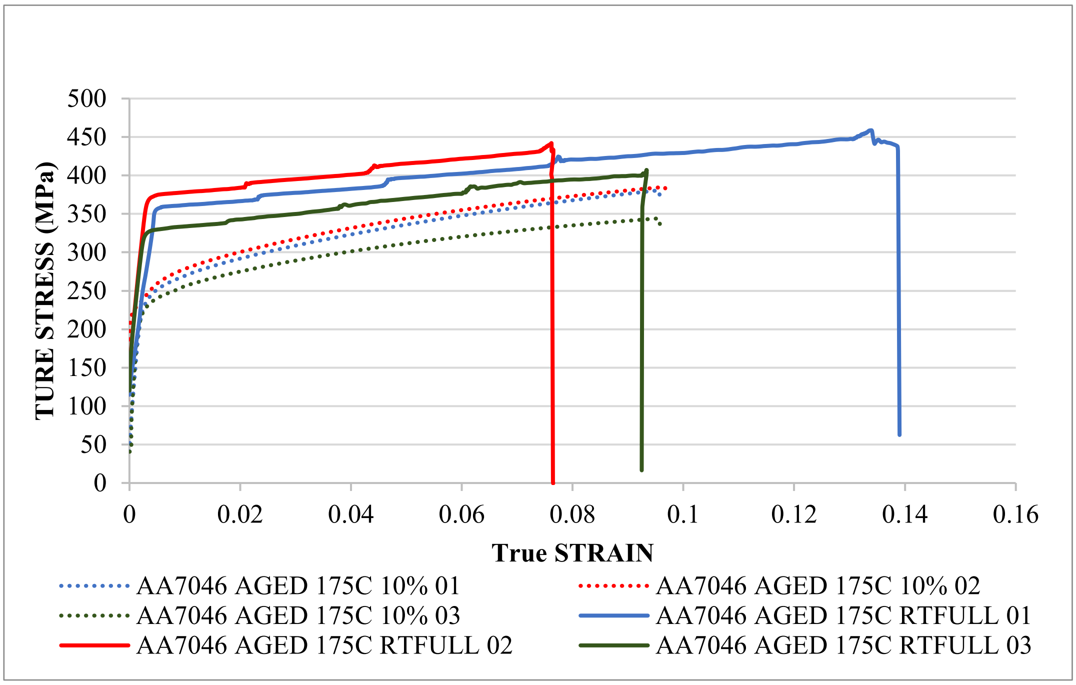



Figure 28: Comparison of warm tensile test and room temperature full tensile test of AA7046 with pre-aged

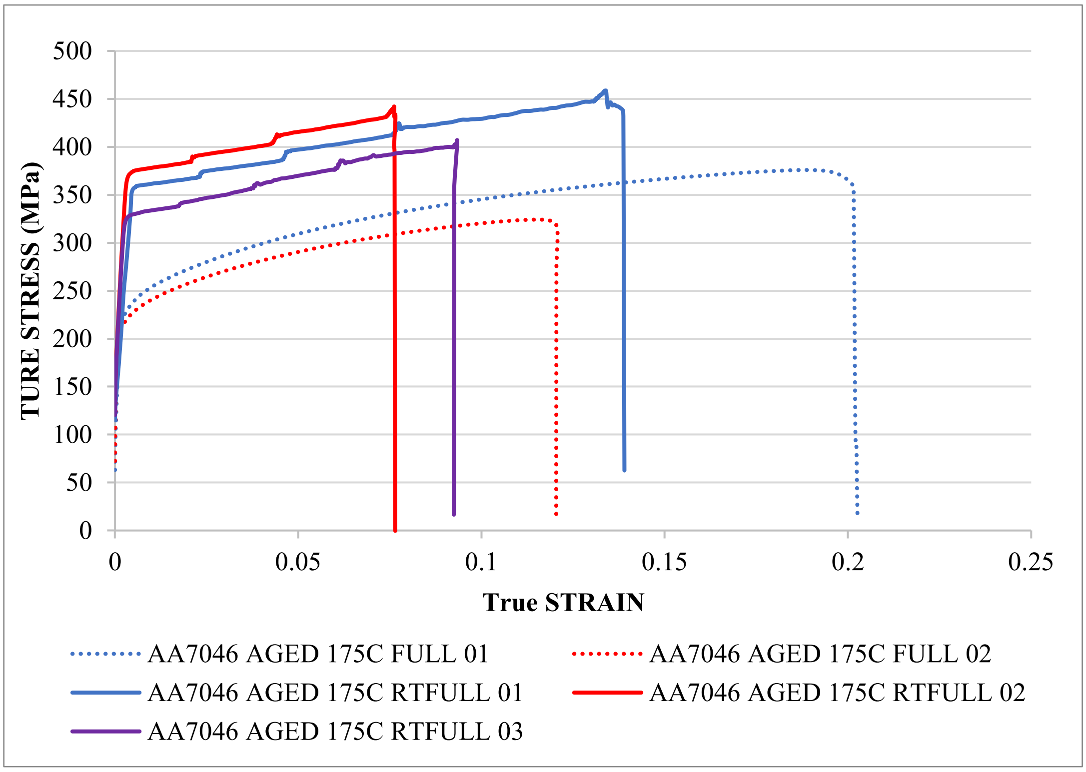



Figure 29: Comparison of "warm tensile test then room temperature full tensile test" and "ONLY full warm tensile test" of AA7046 with pre-aged

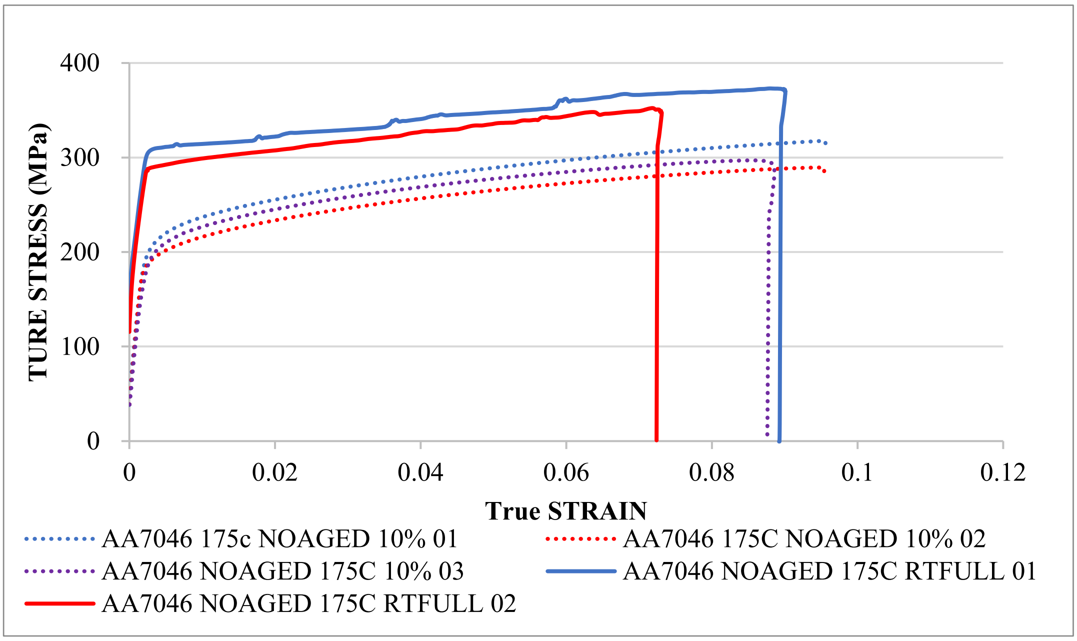



Figure 30 : Comparison of warm tensile test and room temperature full tensile test of AA7046 with pre-aged

**Table 12 The tensile test of AA7046**

| Order | Pre Aged | Final Strain | Rp0.2 | Full test | Final Strain | Rp0.2 | UTS |
|---|---|---|---|---|---|---|---|
| 1 | Yes | No | | Yes | 20,2% | 233 MPa | 376 MPa |
| 2 | | | | | 12,2% | 224 MPa | 324 MPa |
| 1 | No | 10% | 225 MPa | Yes | 9% | 310 MPa | 373 MPa |
| 2 | | 10% | 203 MPa | | 7,3% | 292 MPa | 352 MPa |
| 3 | | 8,8% | 209 MPa | No | | | |
| 1 | Yes | 10% | 250 MPa | Yes | 14% | 360 MPa | 459 MPa |
| 2 | | | 237 MPa | | 9,3% | 374 MPa | 441 MPa |
| 3 | | | 232 MPa | | 7,7% | 329 MPa | 406 MPa |

- Firstly, two sets of high temperature aged AA7046 samples were put together for comparison, one set was tested in full tension at 175°C only and one set was first tensile tested at 175°C until a strain of 10% was reached, air cooled to room temperature and then subjected to a secondary tensile tested (full tension test) at room temperature. The tests exhibited yield strengths of approximately 230-240 MPa at 175°C, with the re-tensile test at room temperature increasing the yield strength by approximately 50%.
- In Chen's paper [38], he also performed the same tensile experiment for AA7046 (10mm/s at 175 ℃ until the sample fractured), compared to his results, my samples had higher UTS and RP0.2, but the final strain was lower

than his value (21%).

- One of a group of AA7046 samples (two samples) that had not been subjected to high temperature pre-aged broke at less than 10% of the strain when subjected to high temperature tensile test and could not be subjected to the next step. The yield strength of this group of samples was also slightly lower than that of the age-treated group (under 175°C testing and room temperature testing).
- None of the strain results for the group without high temperature ageing exceeded 10% for the room temperature re-tensile test and none of the UTS exceeded 400 MPa.

### *3.4.6 The conclusion of tensile test*

- The effect of high temperature ageing or not on alloy AA7021 is not known.
- AA7046 with high temperature ageing exhibited higher yield strength and UTS.
- The strain capacity of AA6016 is its obvious advantage, but his strength is too low, even after high temperature ageing. At different high temperatures (200°C and 225°C) in tension, the strength and strain of the material did not differ much after cooling treatment.
- It is worth mentioning that serration phenomenon was observed in the stress-strain curves of room temperature tensile tests of AA7xxx alloys (AA7046 and AA7021) as evidence of the Portevin-Le Chatalier (PLC) effect. PLC effect belongs to the heterogeneous, permanent and propagative plastic deformation phenomena [35]. The PLC effect results in parallel bands appearing on the surface of the formed sheet, which are considered to be unacceptable surface defects [36].
-

## 3.5 **Micro-hardness testing**

### 3.5.1. The introduction of micro-hardness

Microhardness is a broadly used term referring to the testing of hardness involving materials by using small applied loads. In this testing method, the use of a diamond indenter with a particular shape is used to make an impression called a "test load" or "applied force," which can be at 1-1000 gf (1 gf = 1 pond = 1 p = 9.81 mN), on the material under testing. Because of its specificity, this type of testing is applicable in cases where there is a need to watch for hardness changes on a microscopic level. [18]

The two most commonly used tests to measure microhardness are the Knoop hardness test and the Vickers hardness test. In Europe, a pyramidal Vickers-type (136° interface angle) indenter is usually preferred, which produces a square impression. The equations for Vickers hardness ($H_v$) and Knoop hardness (($H_k$) have the following forms.

$$H_V = 1854.4(\mathrm{P}/d^2)\ \mathrm{kgf}\, mm^{-2}$$

$$H_K = 14228(\mathrm{P}/d^2)\ \mathrm{kgf}\, mm^{-2}$$

The load P and the diagonal length d is measured in grams and microns, respectively, and the Vickers equation we use is based on the surface area of the impression.

In the microhardness test, an indentation is made on the specimen with a diamond indenter by applying a load P (Figure 28). The size d of the indentation is measured with a calibrated optical microscope and the hardness is evaluated as the average stress applied below the indenter.

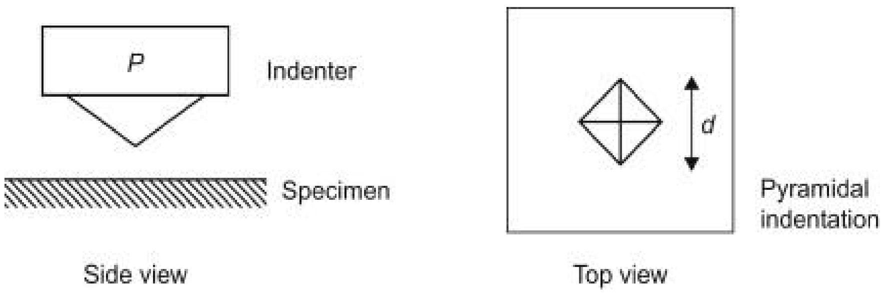



Figure 31 : micro-hardness

The surface of the specimen should be strain free (e.g. electropolished), plane and perpendicular to the indenter axis.[37]

The main potential difficulty concerns the possible dependence of microhardness values ($H_m$) upon test load, [37] So we introduce the Meyer equation, which relates the indentation force P to the diagonal length d of the resulting Vickers-type indentation, as follows:

$$P = kd^n$$

The Meyer index n indicates the strain-hardening characteristics of the material as it undergoes plastic deformation during the test; its value increases as the degree of strain-hardening increases.

Finally, combining the Vickers equation with the Meyer equation, the following expression is obtained:

$$H_V = constant \times d^{n-2}$$

Obviously, if n = 2, which is the conventional Vickers macro hardness test, the gradient of the line $H_m$ becomes 0 and the hardness value is easily independent of the load.

In general, hardness can be understood as resistance to permanent or plastic deformation and can be measured at any desired point on the specimen. The hardness around grain boundaries and defects in the material will show the effect of these on the strength of the metal while still preserving the sample. This makes hardness testing a good test for identifying grain size and microstructure. [38]

### 3.5.2. The process of test

**For mounted AA7046**

Microhardness tests were performed in Polito's laboratory using a Micro-Vickers hardness tester using two samples used in previous studies of metallography. Test loads of 200 gf and 500 gf were selected for each sample, and three experiments were performed for each sample. The surface of the specimen should be flat and perpendicular to the indenter axis. The position of the tested area was placed under a high magnification (40x) microscope lens. Then, we exchange the objective lens with the diamond indenter by turning the disc. A pyramidal indentation shape is produced after the experiment and the microhardness is calculated in the computer software by measuring the area of the indentation shape.

Figure 32 : Hardness testing machines

**For the samples after tensile test**

We performed microhardness tests on all samples (AA6016, AA7021, AA7046) that were previously subjected to tensile tests and eventually fractured. We choose a long fracture section for the test, and if the square impression cannot be observed due to surface problems, we use sandpaper for a simple grinding. Consistent with the previous experiments, each sample was tested 6 times at different locations (3 times at 200g and 3 times at 500g).

### 3.5.3. The review

Before conducting the experiment, I paid a visit to the papers of both Wang [34] and Chen [38],

In Wang's paper 34], he conducted hardness experiments on samples after tensile tests at different high temperatures (from 250 °C to 400 °C ) and found that:

1. for AA6016, the hardness increases slightly from 20 °C to 250 °C. However, from 250 °C to 350 °C they start to decrease, and from 350 °C to 400 °C they decrease sharply.
2. for AA7021 and AA7046, there is a small decrease in hardness from 20 °C to 200 °C; from 200 °C to 250 °C, they increase; and from 250 °C to 300 °C, they both have a large decrease.

In Chen's paper [38], he conducted hardness experiments on AA7046 samples after tensile tests at room temperature and at 200 °Cand found that AA7046 has little effect on hardness at 200 °C.

### 3.5.4. The result of Mico-hardness testing

After sorting the data, it was found that the hardness trends at 200gf and 500gf showed a basic consistency, so only the data at 200gf will be shown in the following line graphs.

**For mounted AA7046**

The following Table shows the results obtained from the experiment:

**Table 13: The value of experiment results for mounted samples**

| Aluminum alloy | Force | HV1 | HV2 | HV3 | HVmedia |
|---|---|---|---|---|---|
| AA7046 Heat-treated mounted | 200 gf | 123.6 | 129.8 | 120.1 | 124.5 |
| | 500 gf | 130.4 | 127.8 | 132.8 | 130.3 |
| AA7046 as-received mounted | 200 gf | 141.6 | 155.6 | 140.7 | 146 |
| | 500 gf | 145.1 | 142 | 145.1 | 144.1 |

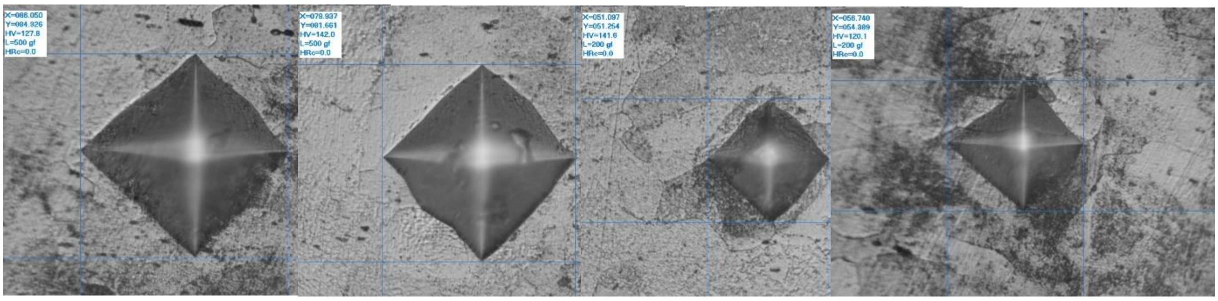



**Figure 33: Hardness test results**

The experiments showed that the hardness of AA7046 after heat treatment showed a decrease.

**For samples after tensile tests**

In the below, Table 14 shows the results of the hardness test for the samples tested in tension

Table 14: the average value of experimental result for the samples after tensile test

| Aluminum alloy | Classification | Tensile test | HV average (200gf) | HV average (500gf) |
|---|---|---|---|---|
| AA7046 | Pre aged | 175°C+$T_{room}$ | 156.9 | 157 |
| | Not pre aged | | 142.9 | 151 |
| | Pre aged | $T_{room}$ | 139.8 | 143 |
| AA7021 | Pre aged | 175°C+$T_{room}$ | 144.8 | 146.7 |
| | Not pre aged | | 137.6 | 146.1 |
| AA6016 | Pre aged | 200 °C+$T_{room}$ | 79.7 | 89.2 |
| | | 225 °C+$T_{room}$ | 97.7 | 98.6 |

- The high temperature pre-aged AA7046 seems to be slightly harder than the not pre-aged AA7046.
- The hardness of group A (10% warm tensile test followed by full tensile test at room temperature) was higher than that of group B (full tensile test at 175°C only) for the same high-temperature aged that both underwent. Possible reasons for this phenomenon: air-cooling after warm tensile test, full test at room temperature is a process of work hardening, when the plastic deformation occurs at recrystallization temperature, the strength and hardness increases to hinder further deformation of the metal.
- The AA7021 hardness experiment did not show a large difference between these two groups of samples.
- For AA6016, the hardness results at the two temperatures are not very different and have a slight increase with increasing temperature.
- In particular, it should be noted that each sample 2 of the two AA6016 groups broke after the first warm tensile test, so there was a significant decrease in hardness in both groups (56 and 61 relative to 200c and 225c, respectively), which suggests that the treatment after warm forming may have had some effect on hardness.

## 3.6 Fractography Studies

### 3.6.1 Experiment Introduction

It was necessary to study the fracture surfaces produced after the tensile tests, and we observed all the samples that had been previously subjected to tensile tests using an optical microscope in the laboratory of the Politecnico di Torino. Under the microscope, we placed the samples along the tensile direction and observed them using a magnification of 6.7x and 20x, respectively. Afterwards, at 6.7x magnification, images of the fracture surfaces of the samples were obtained from the side and from the front in order to measure the angle (shear fracture surface vs. tensile direction) in the software "imagej".

**Figure 34: Microscope used for the experiment**

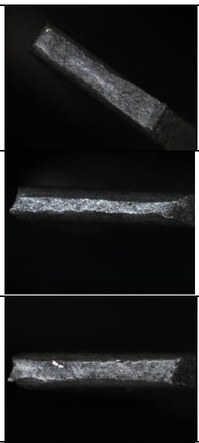
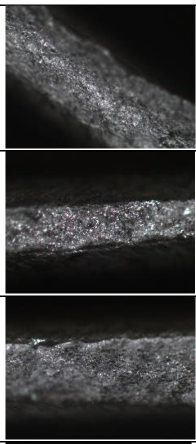
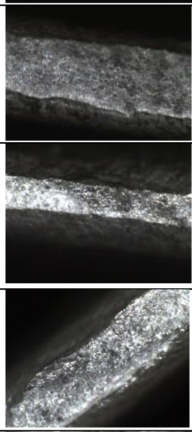
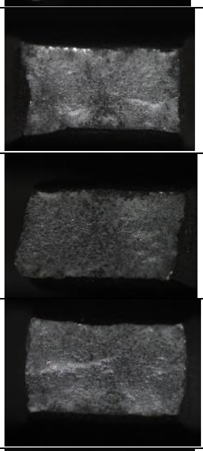
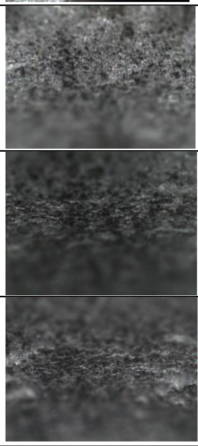
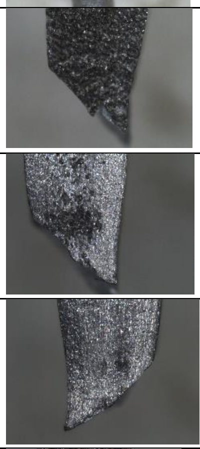
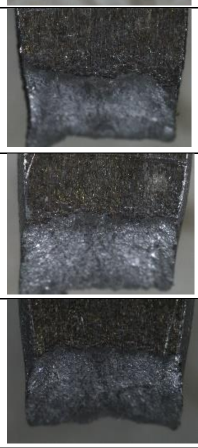
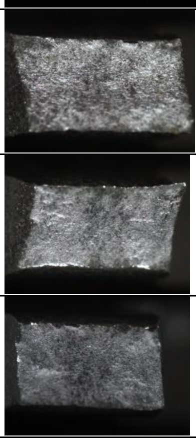
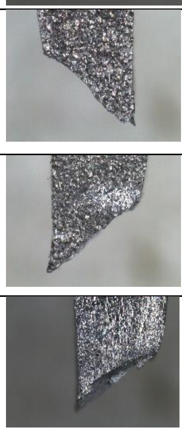
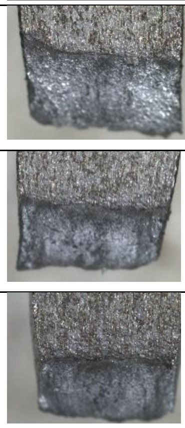
### 3.6.2 Experiment Summary （fracture angle）

I measured the angle of the fractured portion of each specimen (fracture surface vs. tensile direction), and the results are reported below, along with the images I observed under the microscope, which are organized below. Table 15 shows all the values for the angle.

Table 15: The angle value of each speciem

| Specimens | View Direction | Fracture surface angle | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | **Average** |
| AA6016 200°C tensile | Side | 57.24 | 59.41 | 63.35 | **60** |
| | Front | 86.12 | 65.454 | 74.67 | **75.41** |
| AA6016 225°C tensile | Side | 81.18 | 69.37 | 60.19 | **70.25** |
| | Front | 79.627 | 72.104 | 74.161 | **75.30** |
| AA7021 pre-aged | Side | 60.41 | 57 | 55.74 | **57.72** |
| | Front | 87.35 | 90.79 | 94.81 | **90.98** |
| AA7021 not pre-aged | Side | 51.43 | 50.54 | 61.6 | **54.53** |
| | Front | 82.76 | 96.23 | 95.95 | **91.64** |
| AA7046 pre-aged only warm 175°C | Side | 49.85 | 51.43 | / | **50.64** |
| | Front | 92.65 | 66.55 | / | **79.60** |
| AA7046 pre-aged (warm + Troom) | Side | 81 | 62.87 | 70.8 | **71.55** |
| | Front | 84.42 | 87.15 | 69.61 | **80.39** |
| AA7046 no pre-aged (warm + Troom) | Side | 53.44 | 65.36 | 55.75 | **58.19** |
| | Front | 83.36 | 68.72 | 77.05 | **76.38** |

**Table 16: Images of the fracture surfaces of all samples of AA6016 and AA7021**

| Alloy | 6.7X | 20x | Side view | Front view |
|---|---|---|---|---|
| AA6016 (200°C tensile) |  |  |  |  |
| AA6016 (225°C tensile) |  |  |  |  |
| AA7021 pre-aged |  |  |  |  |
| AA7021 not pre-aged |  |  |  |  |

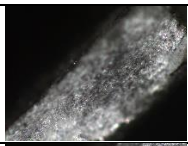
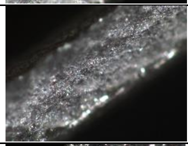
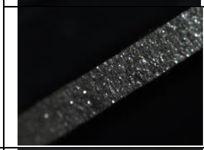
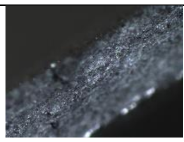
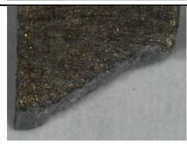
| | | | | |
|---|---|---|---|---|
| AA7046 pre-aged (warm + Troom) |  |  |  |  |
| |  |  |  |  |
| |  |  |  |  |
| AA7046 no pre-aged (warm + Troom) |  |  |  |  |
| |  |  |  |  |
| |  |  |  |  |
| AA7046 pre-aged only warm 175°C |  |  |  |  |
| |  |  |  |  |

**Table 17: Images of the fracture surfaces of all samples of AA7046**

### 3.6.3 Summary

I just used a simple macroscopic approach to look at the fracture surfaces (6.7X and 20X), and as the fracture surfaces were not flat, the angle of sample placement was often adjusted to get a better view of the fracture surfaces.

From the observation of the fractures, they are basically ductile fractures, and in addition, some fractures can be observed to show obvious necking visible to the naked eye.

The side view angles of both sets of samples of AA7021 were smaller, both less than 60 degrees, but the pre-aged AA7021 showed obvious necking shrinkage.

However, in the two sets of samples of AA7046, the side view angle of the not pre-aged AA7046 is smaller, but the fracture surface of the aged AA7046 is flatter.

The side view of AA6016 has a larger angle for both, and the necking phenomenon is obvious.

# 4 CONCLUSION

In this report, three different high-strength aluminum alloys (AA6016, AA7021 and AA7046) were subjected to different heat treatments, tensile tests, hardness tests and fracture surface observations in the hope that some research on the warm forming of aluminum alloys could be obtained. Now, I have made the following conclusions based on the experiments that have been completed and the data from their results.

1. For AA6016, the warm forming at 200 °C and 225 °C did not show much difference in final strength as reported in this experiment, but the experiment showed a slight decrease in the value of final RP0.2 as the temperature of the tensile test increased. For AA7021 and AA7046, for high temperature pre aged and not pre-aged, not much difference in strength is shown.
2. For AA7046, the high temperature pre-aged treated aluminum alloy exhibited a higher (slightly higher) final tensile strength.
   For AA7021, the high temperature pre-aged treated aluminum alloy exhibited essentially similar final tensile strengths to the no pre-aged aluminum alloy.
3. For the metallographic study of AA7046, the two assembled sheets showed approximately the same results under light microscopy, and the precipitates could be analyzed with a more sophisticated microscope.
4. In the three sets of hardness test reports for aluminum alloys, the same aluminum alloy but with different ageing conditions did not show any major differences either.

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