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Experimental Investigation of the Formability Limit Curve (FLC) for AA-2014 Alloy

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Abstract:- AA2014-T4 aluminium alloys are extensively utilized in the defense and aerospace sectors due to their low density, high strength, limited ductility, reduced workability, and excellent corrosion resistance. For materials with low toughness, increasing ductility is crucial, as defects occurring during plastic deformation can limit the forming range and reduce productivity. To enhance the formability of AA2014-T4 sheets, various homogenization conditions were applied, including treatments at 440°C and 500°C for 4 and 12 hours, using both water quenching and furnace cooling methods. The influence of homogenization temperature and time on formability was thoroughly investigated. Under these conditions, several tests were conducted, including the determination of the Forming Limit Curve (FLC), tensile strength measurements, and Limiting Dome Height (LDH) tests to assess formability behaviour. Additionally, the micro-hardness of the AA2014-T4 alloy was evaluated. The experimental data were subsequently used to generate the Forming Limit Curve (FLC). It was observed that the highest level of ductility was achieved when the sheet was homogenized at 440°C for 12 hours, followed by furnace cooling.

Keywords*: AA2014 T4, Elongation, Tensile Strength, Limiting Dome Height, FLC.*

1. Introduction

In recent times, significant advancements have been achieved in the development of lightweight materials for sheet metal applications. However, many challenges have arisen during their subsequent processing. These difficulties usually arise due to a lack of knowledge of the behavior and properties of the material under the conditions encountered in the processing operations, such as stretch forming, drawing, deep drawing, stamping, etc. For materials with low toughness, increasing their ductility is crucial because defects that occur during the plastic deformation of these materials can limit the forming range and reduce productivity. The AA2014 aluminium alloy possesses both low and high strength characteristics, necessitating high working power during fabrication. The AA2014 alloy primarily consists of copper, magnesium, manganese, silicon, and some other elements. It finds widespread use in industries where high strength, hardness, and good formability are essential, such as aviation, shipping, and defines sectors. So, a thorough investigation of the strain rate and temperature dependency of AA2014 would help to understand the deformation behaviour.

The formability of sheet metal refers to the ease with which a blank can be shaped into a useful product. The forming limit curve (FLC) is an effective tool used to assess a material's ability to undergo plastic deformation without defects. It is constructed using pairs of major and minor strain values corresponding to different stress states, ranging from uniaxial to biaxial tension.

Gavgali et al. [1] experimentally studied the effect of homogenization temperature, time, and cooling rate on the hot workability of AA2014 aluminium alloy ingots. The temperatures used were 400°C, 440°C, 480°C, and 500°C. The time durations were 4, 8, 16, and 24 hours. The cooling methods included water quenching (WQ), air cooling, and furnace cooling at different rates. The results showed that the hot workability of AA2014 alloy increases with higher homogenization temperatures but decreases with a higher cooling rate. However, at 510°C, the ductility decreases due to hot brittleness caused by the secondary phase. Based on tensile and torsion tests, the authors recommended the best hot ductility conditions: homogenization at 480°C for 8 hours, followed by cooling at a rate of 12 K/h.

In another study, Gavgali et al. [2] investigated the structural and mechanical differences between the surface and centre of AA2014 alloy ingots after homogenization treatment. The results showed differences in stress and strain values between these regions. The strain values increased from the surface to the center, while the stress values decreased.

Nayan et al. [3] studied different heat treatment methods to homogenize the cast structure and improve the processability of AA2014 alloy. They used empirical methods and light microscopy for their analysis. Their study concluded that copper is the main element that determines the duration of homogenization in AA2014 aluminium alloy. The grain size in an ingot of AA2014 alloy plays a key role in selecting the homogenization method. This is because it affects the diffusion path of the alloying elements.

Saleh [4] studied the effects of homogenization followed by heat treatment on the microstructure and mechanical properties of AA2014 wrought aluminium alloy. The heat treatment included solutionizing, cold deformation rolling, and age hardening at specific temperatures for 1–16 hours. The study concluded that increasing the deformation ratio reduces the recrystallized grain size. This leads to higher strength and hardness.

Sreenath et al. [5] predicted formability using the Formability Limit Diagram. They simulated the Nakazima test with finite element software Pam-Stamp 2G. The experimental values were then compared with the simulation results.

Zahedi et al. [6] studied the forming behaviour of a two-layer metal sheet made from AA1050 aluminium and 1100 copper. The sheets were joined using explosive welding and tested with the hemispherical punch stretching test. Their results showed that the two-layer sheet had higher fracture and necking strain limits when the punch touched the inner aluminium layer.

Ozturk et al. [7] examined different methods for grid marking and strain measurement to determine sheet metal formability. They compared electrochemical etching and serigraphy for grid marking, as well as manual and automated strain measurement. Their study found that the serigraphy method is the best due to its ease of use, low cost, high accuracy, resolution, and contrast. However, for warm forming, electrochemical etching is more suitable.

Sudarsan et al. [8] studied the effect of circular grid size, sheet orientation, punch size, and deformation speed on the forming limit diagram of ultra-thin SS 304 steel. They found that limiting strains changed by about 16% with variations in circular grid diameter, punch size, and deformation speed.

Moshksar et al. [9] plotted in-plane and out-of-plane forming limit diagrams for aluminium 3105. They also studied the effect of lubrication on limit strain and fracture location in out-of-plane deformation samples. The strain level in the out-of-plane FLD was higher than in the in-plane FLD. Under poor lubrication, flow localization and failure occurred near the flange. With good lubrication, failure occurred at the pole.

Hijazi et al. [10] developed a modified LDH test tool for in-situ strain measurements. They introduced a new method for determining forming limit curves (FLCs) using in-situ strain data. The study found that limiting strain values increased with sheet thickness. Anisotropy affected limiting strain on the left side of the FLC, with higher formability at a 45° grain orientation. Lubrication improved formability on both sides of the FLC but had little effect in the plane strain region.

Various experimental and theoretical methods have been used to develop the forming limit diagram (FLD) and evaluate instabilities in sheet metal. Some of the key experimental techniques include uniaxial tensile testing, hydraulic bulging, punch stretching, and the Hecker, Marciniak, Keeler, and Nakazima tests. Among these, the Nakazima test is considered the most effective and beneficial, as it can determine the full range of the FLC. Different strain paths can be obtained by punching specimens using a hemispherical die and circular dies of varying widths. The Nakazima test is widely used in industry and sheet metal testing laboratories due to its simplicity and ability to provide a comprehensive FLD.

This study aims to investigate the effect of homogenization parameters temperature, time, and cooling conditions on the formability of AA2014 aluminium alloy sheets. Unlike previous research that primarily focused on ingots to assess workability, this study evaluates the net impact of homogenization on sheet formability. Uniaxial and biaxial tests are employed to comprehensively analyse the material's forming behaviour

Material and Methods

Determination of Flow curves

The test specimens prepared for FLC (Nakazima test), Uniaxial tensile test, and Hardness test are subjected to homogenisation temperatures of 440°C and 500°C at 4 and 12 hrs in the muffle furnace (Table 1). The specimens were then cooled in one of the following ways: Water- Quenched (WQ) and Furnace-Cooled (FC).

Table 1 Experimental data plan

S.No.	Homogenisation Time	Cooling Conditions	Specimen Sizes (mm)	Total no. of specimens
AA-2014 T4 Condition	–	–	120X120 120X100 120X80 120X60 140X60	5
440°C	4 hours 12hours	Water Quenching Furnace Cooling	120X120 120X100 120X80 120X60 140X60	32
500°C	4 hours 12hours	Water Quenching Furnace Cooling	120X120 120X100 120X80 120X60 140X60	32

Nakazima Test

As per the Nakazima test the specimens were prepared. The specimens used in the tests are 120 X 120, 120 X 100, 120 X 80, 120 X 60, and 140 X 60 mm with a thickness of 1mm is shown in Fig.1. To measure the level of deformation, circular grids of 5 mm diameter as shown in Fig.2. are constructed on the specimens such that the grids should possess resistance to deformation operation and lubrication thus having high accuracy and resolutions. After the homogenisation treatment, the sheet with these grids is then deformed until a fracture or necking is visible using a hydraulic press of 100-ton capacity setup is shown in Fig.3. The true major and minor surface strains corresponding to the different fracture can be calculated with the help of mylar tape as shown in Fig.4. The forming limit curve (FLC) was constructed separating the fracture regions from the safe region. Measurements were made on two specimen areas, as shown fig.6, to determine the limit strains on the dome-shaped specimen region which has undergone enough necking or fracture, while the other is opposite to the necking or fracture area. Two areas were measured: one with a size large enough to include necking or fracture and the other area with a size similar to the opposite. The strain levels close to the fracture were considered to be inadequate or to have experienced necking, while the rest were considered to be safe strain values. The purpose of measuring the opposing sides of fractures or necking is to determine the details of safe forming limit and the specifics of incipient necking. These strain values are referred to as safe strain, incipient necking, and necking values.

Measurement of Limiting Dome Height

It is the height measured from the centre of the dome formed to the surface of the top die plate as shown in Fig. 6 The dome height is measured by using a digital vernier callipers. Dome height measurements are noted for specimens of different widths.

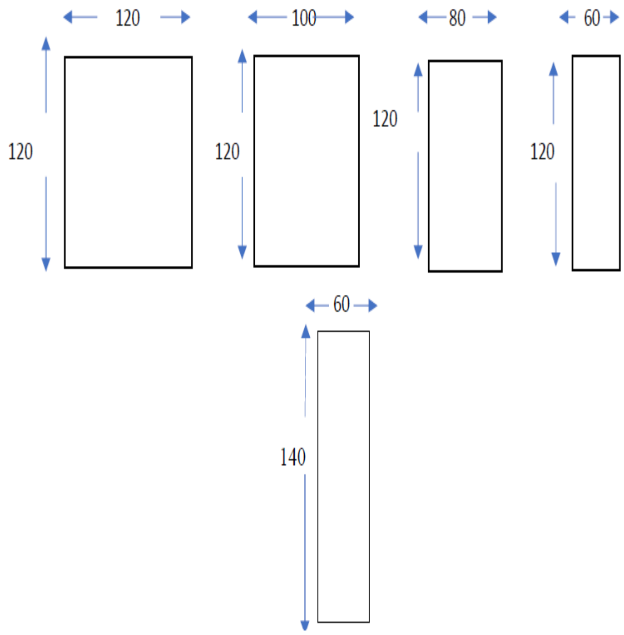

Fig.1: FLC test specimens (mm)

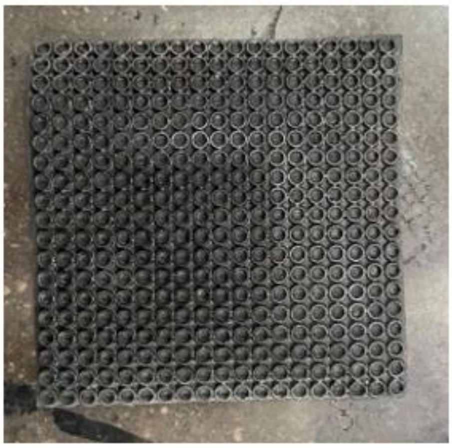

Fig.2: Grid marking rubber Stamp

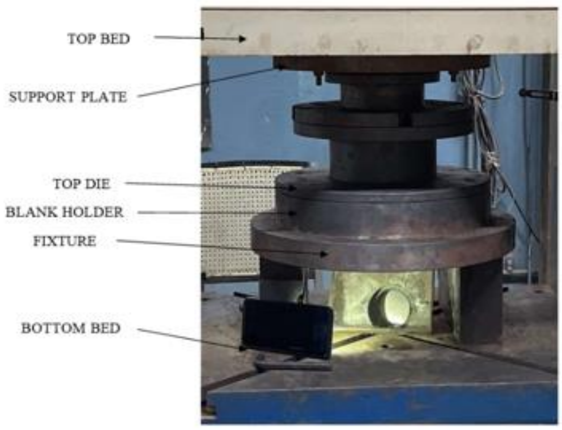

Fig.3: Tool Assembly for LDH setup

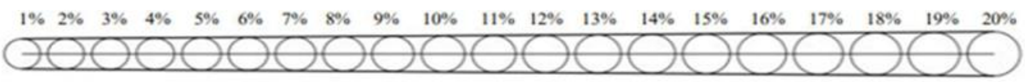

Fig.4: Mylar Tape

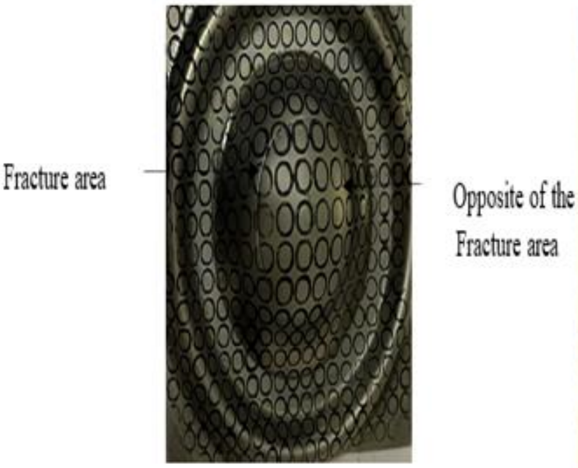

Fig.5: Fracture and opposite of the Fracture area

Fig.6: Measurement of LDH

Uniaxial Tensile test

The Uniaxial Tensile Test are done as per ASTME8/E8M-21 on a universal testing machine. The specimens from Aluminium alloy AA2014 sheets of 1.0 mm thickness are cut along the rolling direction, and transverse direction to determine the material properties at different homogenisation temperatures.

Fig.7 Standard specimens machined for Tension test (all dimensions are in mm)

Hardness Test

The microhardness was measured using a Vickers Hardness test that forms a diamond indenter on to the specimen when a load of 500 gm is applied for 30 seconds. It is one of the standardised procedures (ISO 6507, ASTM E92, ASTM E384). The hardness test is performed for five times on each specimen and the mean value is taken.

2. Results and Discussion

The major and minor strains of each ellipse of stretched sheet metal samples of various specimen widths are calculated. The ellipse from each sample with the maximum strain is chosen for the FLC plot. The graph between major strain and minor strain has been plotted after choosing the maximum major strain, as illustrated in the Fig. 8 for 4hrs, 12hrs duration at 440°C, 500°C and water quenched, furnace cooling. After drawing FLC, the safe zone values of major and minor strain for the rest of the homogenised samples are tabulated in Table .2

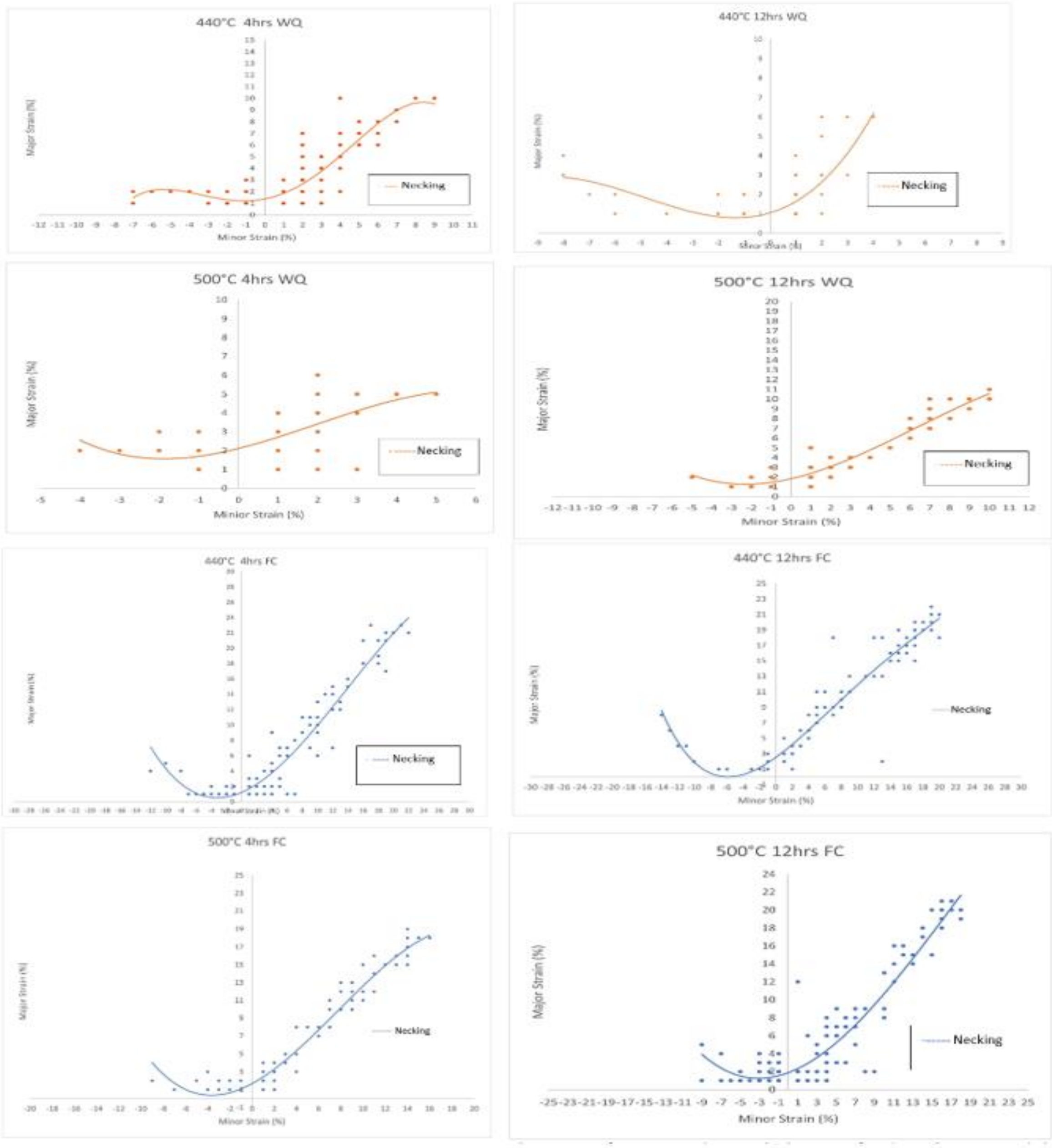

Fig.8 : FLC of AA 2014 homogenised conditions of Water Quenched and Furnace Cooled

Table. 2 Major and Minor strains (%) values based on FLC Curves

Homogenisation Treatment	Major Strain (%)	Minor Strain (%)
440°C-4hrs WQ	2% to 9.5%	1% to 9%
440°C-12hrs WQ	1.5% to 6%	1% to 6%
500°C-4hrs WQ	2.5% to 5%	1% to 5%

500°C-12hrs WQ	2.5% to 10.5%	1% to 10%
440°C-4hrs FC	1.5% to 23%	1% to 21%
440°C-12hrs FC	3% to 21%	1% to 20%
500°C-4hrs FC	2% to 18%	1% to 16%
500°C-12hrs FC	2% to 21%	1% to 17%

From the Table 2, it was observed that, Furnace cooling (FC) results in higher strain values for both major and minor strain compared to water quenching (WQ). Increasing the homogenisation holding time from 4hrs to 12hrs generally broadens the major and minor strain ranges, particularly under FC. The highest recorded strain values are found under 440°C-4hrs-FC (1.5% to 23%), indicating that slow cooling helps maintain greater strain tolerance.

Table.3 LDH of water quenched, furnace cooled and AA2014-T4 specimens

S.No.	Specimen Sizes (mm)	AA-2014 T4 (mm)	440°C -4hr (WQ) (mm)	440°C -12hr (WQ) (mm)	500°C -4hr (WQ) (mm)	500°C -12hr (WQ) (mm)	440°C -4hr (FC) (mm)	440°C -12hr (FC) (mm)	500°C -4hr (FC) (mm)	500°C -12hr (FC) (mm)
1	120 X 120	33.9	34.9	32.56	33.8	35.7	36.2	40.6	37.7	36.1
2	120 X 100	31.0	31.28	31.54	32.55	33.8	36.88	40.3	35.7	34.34
3	120 X 80	30.1	32.0	32.16	32.77	34.3	33.84	33.6	32.9	32.3
4	120 X 60	31.5	34.2	33.41	32.14	31.81	31.9	33.1	31.4	33.14
5	140 X 60	29.8	31.5	31.5	32.12	31.22	32.88	33	32.55	31.1

From Table 3, It was observed that the dome height increased with the increase in width of the specimen and also it is observed that the dome height has increased comparatively for 440°C-12hrs furnace cooled followed by 440°C-4hrs furnace cooled than other cooling conditions and temperatures. Water quenched samples show low LDH, indicating contraction due to rapid cooling and stress buildup. Furnace-cooled samples retain higher LDH, suggesting stress relaxation and grain stabilization. Higher temperatures (500°C) lead to slight expansion, likely due to increased diffusion and phase transformations. Longer soaking times (12hr) contribute to increased LDH indicating grain coarsening and reduced residual stress. Furnace cooling (FC) results in larger dimensions compared to water quenching (WQ) across all specimens

Table 4. Tensile test results of 440°C ,500°C-4hrs &12hrs Water Quenching and Furnace cooling

S.No.	TEST PARAMETER	UNITS	RESULTS			
			440°C-4hrs Water Quenching		440°C-12hrs Water Quenching	
			Along the rolling direction	Perpendicular to the rolling direction	Along the rolling direction	Perpendicular to the rolling direction
1	Tensile Strength	MPa	323.71	321.02	315.45	326.36
2	Yield Strength	MPa	190.7	203.85	192.15	200.96
3	Elongation	%	14.34	16.2	10.8	16.68
			500°C-4hrs Water Quenching		500°C-12hrs Water Quenching	
1	Tensile Strength	MPa	402.24	415.39	393.91	410.45
2	Yield Strength	MPa	248.59	263.03	257.8	255.1
3	Elongation	%	15.1	18.26	12.8	12.48
			440°C-4hrs Furnace Cooling		440°C-12hrs Furnace Cooling	
1	Tensile Strength	MPa	197.48	200.14	196.2	194.9
2	Yield Strength	MPa	150.54	142.72	136.34	137.58
3	Elongation	%	17.96	17.4	19.8	19.78
			500°C-4hrs Furnace Cooling		500°C-12hrs Furnace Cooling	
1	Tensile Strength	MPa	188.66	194.23	186.79	190.3
2	Yield Strength	MPa	124.68	129.48	128.82	128.49
3	Elongation	%	19.22	15.54	17.4	19.5

From the Table 4, it was observed that, Tensile and yield strengths are slightly higher along the rolling direction than perpendicular to it. Hence this effect can be neglected. Water-quenched samples exhibit higher tensile and yield strength than furnace-cooled samples. Rapid cooling suppresses diffusion, leading to finer grain structures and retained residual stresses. This results in higher strength but reduced ductility due to increased internal stresses and potential brittle phases. Furnace-cooled samples have higher elongation (ductility), but lower strength. Slow cooling allows more diffusion and stress relaxation, leading to coarser grains. This decreases strength but improves elongation, making the material more ductile.

Higher strength values are observed at 500°C compared to 440°C (for water-quenched samples) and at 500°C, elongation decreases slightly compared to 440°C in most cases. Higher temperatures allow for better solutionizing, leading to the dissolution of precipitates and improving strength. However, prolonged exposure can cause over-aging, reducing ductility and toughness. For both 440°C and 500°C treatments, 12-hour solutionizing time slightly reduces tensile and yield strength compared to 4-hour treatment and Elongation increases with longer ssolutionizing, times.

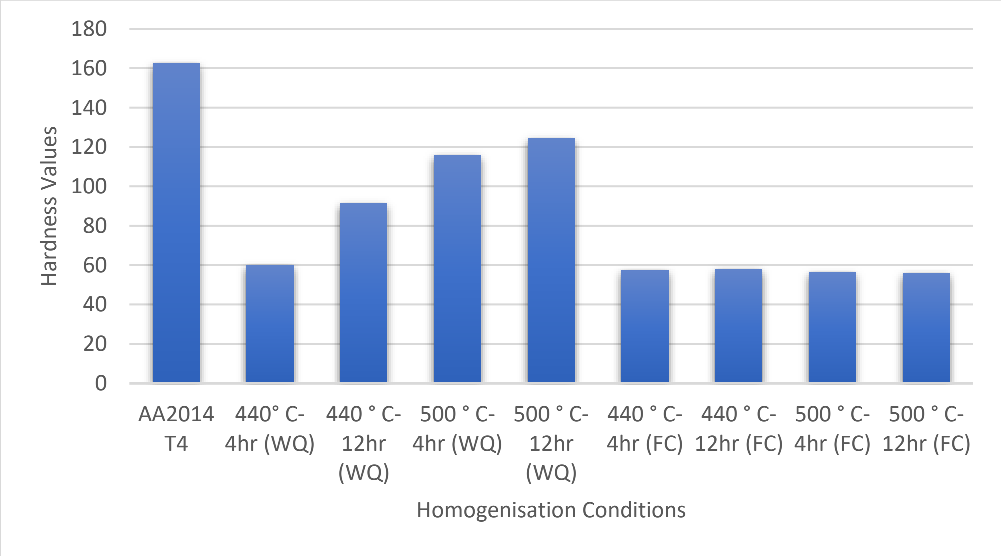

Fig.9: Variation of hardness with homogenisation time and temperature

It was observed from Fig.9 that, WQ samples have higher hardness than FC samples because Rapid cooling retains a finer grain structure and prevents softening and Hardening phases (such as Al-Cu precipitates) are retained in the microstructure, increasing strength. 500°C samples have slightly higher hardness than 440°C samples under WQ conditions because, Higher solutionizing temperature dissolves more strengthening phases, which are retained after quenching and leads to improved precipitation hardening upon cooling. At 500°C under FC conditions, hardness drops significantly, indicating over-aging effects, where strengthening precipitates coarsen and lose their hardening ability.

Conclusions

In this research work, FLC, LDH and Mechanical Properties of AA2014-T4 sheet and at different homogenised conditions such as 440°C and 500°C for 4 and 12hr followed by two different cooling conditions such as water quenching and furnace cooling were studied. Based on the experiments performed, the following conclusions are drawn.

From the FLC graphs of the AA2014-T4 it was found that the maximum deformation was attained at 440°C-4 and 12 hours of furnace cooling with a major strain of (3% to 21%) and minor strain of (1% to 20 %). It was also observed from the Limiting Dome height test that the maximum dome height of (40.6 mm) is achieved at 440°C-12hrs furnace cooling. From the tensile test it was also observed that 440°C-12hrs furnace cooled specimens has the highest percentage of elongation i.e. 19.80% along the rolling direction. In addition to this lowest hardness was observed for 440°C-12hrs furnace cooled specimen.

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