Optimized T6 process parameters for Aluminum and its alloys

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Abstract
This paper investigates the impact of optimized T6 heat treatment parameters (Solution Treatment + Ageing) on the metallurgical and mechanical properties of sand-casted and gravity die-casted (GDC) aluminum alloys. The primary focus is on the hardness and microstructural characteristics—such as grain size distribution, microstructure analysis, and silicon needle segregation within the aluminum matrix—of AlSi7Mg, AlSi10Mg, AL356, AC2B, and AC4B alloys. The optimized T6 precipitation hardening process involved solution treatment at 530°C for 5 hours, followed by quenching in water at 60–70°C. Subsequently, the specimens underwent ageing at 170°C for 4.5 hours to stabilize the alloying elements at specific grain boundaries.

Post-treatment, Vickers and Brinell hardness tests were conducted to assess the mechanical properties, and metallurgical microscopy was employed for surface analysis. The optimized T6 process demonstrated superior hardness and impact properties compared to traditional T6 parameters. Additionally, the optimized process reduced the required treatment time for both solution treatment and ageing by nearly 50% while maintaining or enhancing metallurgical performance. This study provides critical insights into the influence of optimized heat treatment on aluminum alloys used in sand casting and gravity die casting applications.

Index Terms: Optimized T6 heat treatment, Solution treatment, Ageing, Sand casting, Gravity die casting, Aluminum alloys, AlSi7Mg, AlSi10Mg, AC4B, AC2B, Hardness (Vickers/Brinell).

I. INTRODUCTION

T6 Solution Treatment and Ageing refers to a heat treatment process commonly used to enhance the mechanical properties of aluminum alloys, particularly those in the 6xxx and 7xxx series. This process involves three main steps:
1. Solution Treatment - The alloy is heated to a temperature just below its melting point (around 480–540°C for most aluminum alloys). This temperature allows the alloying elements (like Mg, Si, Cu) to dissolve into the aluminum matrix, forming a homogeneous solid solution. The material is then rapidly quenched (usually in water or air) to retain the alloying elements in a supersaturated solid solution.
2. Quenching - Rapid cooling "freezes" the dissolved elements in place, preventing the formation of coarse precipitates. This step ensures the material remains in a metastable state, primed for the next stage of ageing.
3. Artificial Ageing - The quenched alloy is reheated to a lower temperature (typically 120–200°C). This controlled heating allows the alloying elements to precipitate out in a fine, dispersed manner, forming strengthening phases. The ageing process enhances mechanical properties such as yield strength, tensile strength, and hardness, often at the expense of some ductility.
Key Benefits of T6 Treatment: Increased strength and hardness. Enhanced fatigue resistance. Improved corrosion resistance (depending on the alloy).
Applications: Aerospace components. Automotive parts (wheels, frames). Structural applications in construction. Sporting goods and bicycles.

Fig.1 Sand casted Swing Arm

Fig. 2 Gravity die casted BFT

II. LITERATURE SURVEY

A) SAMPLE PREPARATION-

The specimens have been obtained from AlSi7/10Mg and A356 (Sand and Die casted). Composition of specimen is given in table 1. Specimens were first decoaring from moulds after pouring then fettled, milling and finished by tools and milling machine. Specimens were loaded in furnace with fixture at 530 Deg C temperature. Size of furnace heating chamber was 450*450 mm and quenching tank with 100 Litres capacity includes 6 heaters and water mixing motorised setup. Furnace used was electrically fired with 10 heating elements surrounding the chamber having heating capacity up to 600°C. Fig 1 shows T6 process setup used for trial.

B) CHEMICAL COMPOSITION %

Specification – Table 1

Chemical symbols	Chemical composition, % (mass fraction)												
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Others [a]		Aluminium
												Each	Total	
Al Si7Mg	6,5 to 7,5	0,55 (0,45)	0,20 (0,15)	0,35	0,20 to 0,65 (0,25 to 0,65)	—	0,15	0,15	0,15	0,05	0,05 to 0,25 (0,05 to 0,20)	0,05	0,15	Remainder
Al Si10Mg	9,0 to 11,0	0,55 (0,45)	0,10 (0,08)	0,45	0,20 to 0,45 (0,25 to 0,45)	—	0,05	0,10	0,05	0,05	0,15	0,05	0,15	Remainder

Actual – Table 2

Chemical composition	Alloying element in percentage									
AlSi7Mg	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	Pb	Sn	Al
	0.011	6.78	0.62	0.008	0.18	0.13	0.005	0.100	0.009	0.012	Remaining

Table 1 – Specification Composition of AlSi7Mg/10Mg
Table 2 – Actual Composition of AlSi7Mg

Specification and actual – Table 3

Open with

SPECTRO

Sample Results

Sample Result Name	Type	Measure Date Time	Recalculation Date Time	Origin
INGOT-A356/AMIT WASNIK	Unknown	26-07-2024 12:15	26-07-2024 12:19	Measured

Method Name	Check Type	Check Status	Correction Type	Outlier Test Type
Al-20-M	None	Not Used	None	None

Status
Not Used

Sample Name	checked by	Temperature	Humidity	CRM ID	Grade Norm	Grade ID
INGOT-A356	AMIT WASNIK					

	Si Conc %	Fe Conc %	Cu Conc %	Mn Conc %	Mg Conc %	Cr Conc %	Ni Conc %	Zn Conc %	Ti Conc %	Be Conc %
1	6.84	0.0965	0.0014	<0.00030	0.384	<0.00030	0.0064	<0.00100	0.125	<0.00005
2	6.90	0.0931	0.0011	<0.00030	0.395	<0.00030	0.0063	<0.00100	0.122	<0.00005
3	6.97	0.0919	0.00053	<0.00030	0.373	<0.00030	0.0061	<0.00100	0.124	<0.00005
Mean	6.90	0.0939	0.0010	<-0.0017	0.384	<-0.00003	0.0063	<-0.0017	0.124	<0.000008
SD	0.0651	0.0024	0.00042	0.000000	0.0112	0.000000	0.00014	0.000000	0.0017	0.000000
RSD	0.944	2.54	42.16	0.000000	2.92	0.000000	2.18	0.000000	1.36	0.000000

	Bi Conc %	Ca Conc %	Cd Conc %	Co Conc %	Ga Conc %	Li Conc %	Na Conc %	P Conc %	Pb Conc %	Sb Conc %
1	<0.00100	0.0020	<0.00010	<0.00050	0.0117	<0.00010	0.0027	<0.00100	<0.00050	<0.0030
2	<0.00100	0.0021	<0.00010	<0.00050	0.0114	<0.00010	0.0028	<0.00100	<0.00050	<0.0030
3	<0.00100	0.0020	<0.00010	<0.00050	0.0113	<0.00010	0.0029	<0.00100	<0.00050	<0.0030
Mean	<-0.0022	0.0020	<-0.00094	<-0.00059	0.0115	<0.00002	0.0028	<-0.0014	<-0.00027	<0.0012
SD	0.000000	0.00004	0.000000	0.000000	0.00024	0.000000	0.00010	0.000000	0.000000	0.000000
RSD	0.000000	1.86	0.000000	0.000000	2.13	0.000000	3.66	0.000000	0.000000	0.000000

	Sn Conc %	Sr Conc %	V Conc %	Zr Conc %	Bg %	Al Conc %
1	<0.00100	0.0148	0.0100	0.0013	--	92.5
2	<0.00100	0.0149	0.0098	0.0012	--	92.4
3	<0.00100	0.0150	0.0098	0.0013	--	92.4
Mean	<-0.0058	0.0149	0.0099	0.0013	--	92.5
SD	0.000000	0.00014	0.00015	0.00006	--	0.0561

Chemical composition reports A356 Ingot			
Element	Symbol	A356 Specified values %	A356 Ingot - Actual values
Silicone	Si	6.5 - 7.5	6.9
Iron	Fe	0.20 max	0.09
Copper	Cu	0.20 max	0.001
Manganese	Mn	0.10 max	<-0.0017
Magnesium	Mg	0.25 - 0.45	0.384
Zinc	Zn	0.10 max	<-0.0017
Titanium	Ti	0.20 max	0.124
Strontium	Sr	0.05 max	0.0149
Aluminium	Al	Remaining	Remaining

Table 3 – Specification and Actual Composition of A356

C) MECHANICAL PROPERTIES

Specification -

Alloy group	Alloy designation	Temper designation	Tensile strength R_m MPa min.	Proof stress $R_{p0,2}$ MPa min.	Elongation A [a] % min.	Brinell hardness HBW min.
AlSi7Mg	Al Si7Mg	F	140	80	2	50
		T6	220	180	1	75
	Al Si7Mg0,3	T6	230	190	2	75
	Al Si7Mg0,6	T6	250	210	1	85
AlSi10Mg	Al Si9Mg	T6	230	190	2	75
	Al Si10Mg	F	150	80	2	50
		T6	220	180	1	75
	Al Si10Mg(Cu)	F	160	80	1	50
		T6	220	180	1	75

Mechanical properties specification of AlSi7/10Mg

3	Tensile Strength	Tensile M/C	245 N/mm² Min.
4	Yield strength	Tensile M/C	167 N/mm² Min.
5	% elongation	Tensile M/C	8 % Min.

Mechanical properties specification of A356

Actual mechanical properties results of AlSi7Mg -

5	% Elongation	Tensile m/c	-----	Middle 01 -0.65 % Middle 02 -0.86 % Left Hand Side-03 - 0.29 % Left Hand Side - 04-0.71 % Left Hand Side - 05 - 1.13 % Left Hand Side - 06- 1.01 % Left Hand Side - 07 - 1.24 % Left Hand Side- 08 - 1.14% Right Hand Side - 09 - 1.06 % Right Hand Side- 10- 1.38% Right Hand Side - 11 - 1.08 % Right Hand Side - 12 - 0.50 % Right Hand Side - 13 - 0.48% Right Hand Side - 14 - 1.40 %	For Ref.
6	Raw material	Approved source	Raw material vendor	Mill tc required	For final approval

7	Chemical Composition % ELEMENTS												Remarks
	MATERIAL	Cu	Si	Mg	Zn	Fe	Mn	Ni	Ti	Pb	Sn	Al	
Spec.	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	
Obsb.	Swing arm	0.011	6.78	0.62	0.008	0.18	0.130	0.005	0.100	0.009	0.012	Bal.	OK

Obsb.
Conclusion : # This Report only for reference.

EVALUATED BY	PREPARED BY	CHECKED BY	APPROVED BY	Final Decision	
	[signature]	[signature]	[signature]	Accepted / Rejected	For ref.

Tensile strength Mpa							
Area	Readings						Mean
Middle	273	269					271
Left Hand side	275	270	282	288	302	291	284.7
Right Hand Side	286	292	284	382	229	293	294.3

Yield strength Mpa							
Area	Readings						Mean
Middle	278	274					276
Left Hand side	284	281	255	265	270	266	270.2
Right Hand Side	263	261	257	273			263.5

% Elongation							
Area	Readings						Mean
Middle	0.65	0.86					0.755
Left Hand side	1.29	1.71	1.13	1.01	1.24	1.14	1.3
Right Hand Side	1.06	1.38	1.08	1.20	1.08	1.40	1.2

Actual Mechanical properties results of A356

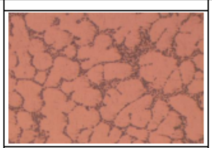
CIT
MATERIAL RESEARCH
CIT, JAIPUR

MATERIAL EVALUATION REPORT

FORMAT NO: IMDM:CIT:VI:MR:FF:03, Rev: 00
MIR NO. : MIR_ACJB_10713_24/00
Receiving Date: 11.09.2024
LTR NO.:MET-4098
DATE: 26-09-2024

Type of material	Al	Quantity received	04 Nos.	Quantity Evaluated	04 Nos.	Project/Model	ACJB
Part Name	BRIDGE FORK BOTTOM					Sample Stage	Proto
Part No.	--					Specification	--
Vendor:	Customer : PROTO		RM Source :--			Reference Standard	--

Background:Sample recievd to check metallurgical parameters & mechanical properties.

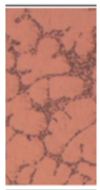
S. NO.	Parameters	Test	Specification	Observation	Remarks
1	Hardness	Load - 100 kgf in rockwell 'B' scale	HRBW	47 – 48 HRBW	For ref.
2	Microstructure	Microscope at 100X Mag.	'Uniformly distributed Si particles in the Al matrix	 Uniform Si Dendrites in the Al matrix observed	OK
3	Tensile Strength	Tensile M/c	--	'A2-1 : 218 Mpa A2-2 : 218 Mpa A2-3 : 218 Mpa A3-1 : 214 Mpa Avg. : 214 Mpa	OK
4	Yield Strength	TENSILE M/C	--	'A2-1 : 286 Mpa A2-2 : 279 Mpa A2-3 : 285 Mpa A3-1 : 283 Mpa Avg. : 283 Mpa	OK
5	% Elongation	Tensile M/c	--	A2-1 : 9.3 % A2-2 : 6.3 % A2-3 : 10.9 % A3-1 : 8.6 % Avg.: 8.8 %	OK
6	Raw material	Approved Source	Raw material Vendor	QAV is required	For final approval

7	Chemical Composition % Elements										Remarks
	material	Cu	Si	Fe	Mn	Mg	Cr	Ti	B	Pb	
Spec.	--										
Obsd.	HMCL	0.0007	7.10	0.098	0.005	0.3	0.0002	0.126	0.0002	0.0005	For ref.

Conclusion : - # This report is for your ref. only.

EVALUATED BY	Prepared by	Checked by	Approved by	Final Decision	
	[signature]	[signature]	[signature]	Accepted / Rejected	For Ref.

47 – 48 HRBW



i Dendrites in the Al matr

'A2-1 : 218 Mpa
A2-2 : 218 Mpa
A2-3 : 218 Mpa
A3-1 : 214 Mpa
Avg. : 214 Mpa

'A2-1 : 286 Mpa
A2-2 : 279 Mpa
A2-3 : 285 Mpa
A3-1 : 283 Mpa
Avg. : 283 Mpa

A2-1 : 9.3 %
A2-2 : 6.3 %
A2-3 : 10.9 %
A3-1 : 8.6 %
Avg.: 8.8 %

- Mechanical properties achieved as per the specification. The %El is 8.8%.
- As per the MIR, the hardness and mechanical properties achieved on actual component.

D) PROCESS DETAILS-

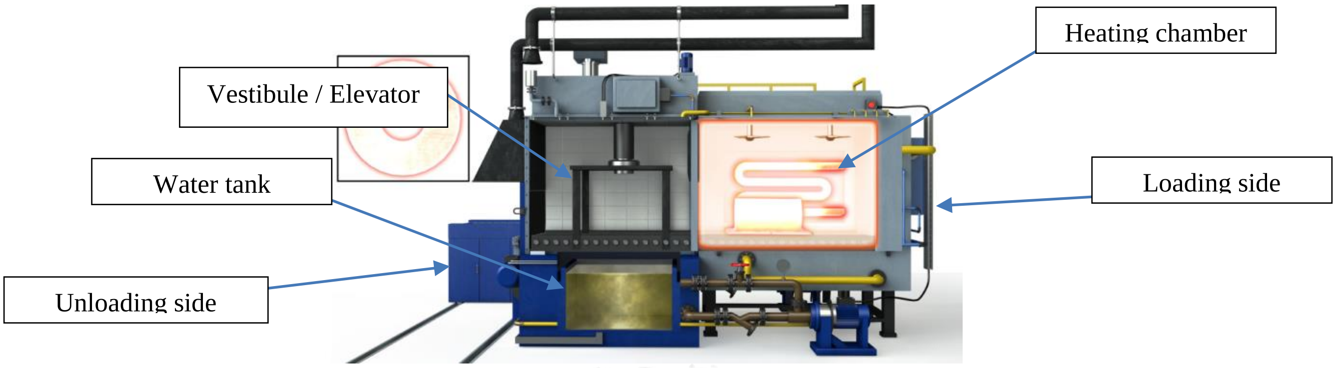


Fig. 1. T6 process setup

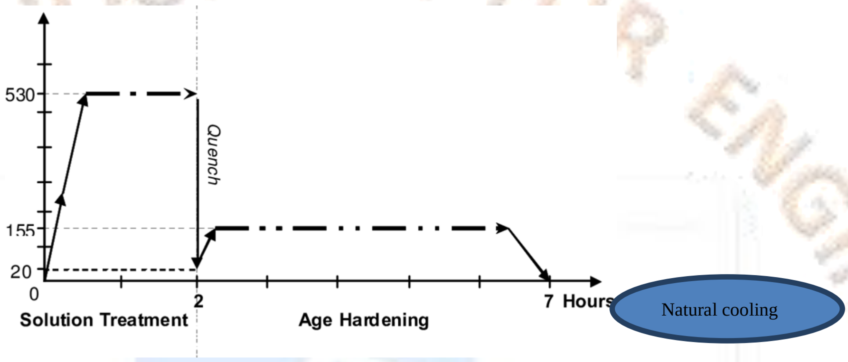


Fig. 2. T6 process segments setup

T6 Solution Treatment and Ageing is a heat treatment process that strengthens aluminum alloys, particularly those in the 6xxx and 7xxx series. The process involves three main segments:

* Solution Treatment: The alloy is heated to a specific temperature and held there for a set time to dissolve alloying elements into the solid solution.
* Quenching: The alloy is rapidly cooled to room temperature to trap the alloying elements in the solid solution.
* Ageing: The alloy is held at a specific temperature for a set time to allow precipitation of strengthening phases.

In our recent experiments, we conducted a thermo-chemical cycle comprising four different segments with varying time and temperature parameters. This aimed to achieve the maximum hardness range as specified in the standard. The experimental conditions are detailed in Table 2.
For comparison, Table 1 outlines the old T6 process parameters with its four segments. The differences between the old and new (optimized) process parameters are highlighted in Tables 1 and 2.

T6 SEGMENT DETAILS OLD process parameters

Segment Number	Temperature	Time	Gas or other Supplied
Segment 1	530°C	8 Hrs after reaching 530°C	Not required
Segment 2	30°C	20 min after solution	Water plain
Segment 3	170°C	8 Hrs after reaching 170°C	Not required
Segment 4	Room temperature	after water quenching	Not required

Table 1- Segment wise details

T6 SEGMENT DETAILS optimised process parameters

Segment Number	Temperature	Time	Gas or other Supplied
Segment 1	530°C	5 Hrs after reaching 530°C	Not required
Segment 2	50-60°C	20 min after solution	Water plain
Segment 3	170°C	4.5 Hrs after reaching 170°C	Not required
Segment 4	Room temperature	after water quenching	Not required

Table 2- Segment wise details

III. RESULTS & DISSCUSION-

A) SURFACE HARDNESS

Preparing the microstructure of T6-treated aluminum alloys for analysis involves several steps, ensuring that the microstructure is properly revealed for microscopic examination. Here's a detailed procedure:
1. Sample Preparation
Cutting: Use a low-speed precision saw with a lubricant or coolant to avoid overheating, which can alter the microstructure.
Mounting: Embed the sample in a mounting resin (cold or hot mount). Hot mounting uses thermosetting resins, while cold mounting is ideal for heat-sensitive materials.
2. Grinding - Use a series of silicon carbide (SiC) abrasive papers with progressively finer grits (e.g., 240, 400, 600, 800, 1200). Apply water as a lubricant and coolant during grinding to minimize heat and deformation. Rotate the sample by 90° between each grit to remove scratches from the previous step.
3. Polishing - Initial Polishing: Use diamond suspensions (6 µm or 3 µm) on a hard polishing cloth.
Final Polishing: Use finer diamond suspension (1 µm or 0.25 µm) or colloidal silica (0.05 µm) for a mirror-like finish. Ensure proper cleaning between each polishing step to avoid cross-contamination.
4. Etching - Purpose: Etching reveals the microstructure, including grains, precipitates, and second-phase particles.
Common etchants for aluminum alloys include:
Keller's Reagent: Composition: 2.5 ml HNO_3, 1.5 ml HCl, 1.0 ml HF, and 95 ml distilled water. Etch time: 10–30 seconds, depending on the alloy. Modified Poulton's Reagent: Composition: 30 ml HCl, 5 ml HNO_3, 1 ml HF, and 100 ml distilled water. Used for detailed grain structure. Immerse the polished sample briefly and rinse immediately with water and methanol, then dry with warm air.

BRINELL HARDNESS PLOT

Specimen Number	Old process results	Optimised process results
	AlSI7MG/10Mg	AlSI7MG/10Mg & A356
1	40-50 HRB	48-52 HRB
2	41-50 HRB	46-55 HRB
3	40-52 HRB	48-58 HRB
4	38-53 HRB	45-57 HRB

Table 5- Surface hardness comparison

B) MICROSTRUCTURE -

The microstructure of T6 aluminum refers to the internal arrangement of grains and phases in aluminum alloys treated to the T6 temper. T6 involves solution heat treatment, quenching, and artificial aging to optimize the material's strength and mechanical properties. Here's a detailed breakdown of the microstructure for typical aluminum alloys like 6061-T6 or 7075-T6:

1. Matrix Phase
The primary microstructure consists of a solid solution of aluminum (Al) with alloying elements like magnesium (Mg), silicon (Si), copper (Cu), or zinc (Zn) dissolved in it.
The grain boundaries are well-defined, with grain size depending on the processing conditions.
2. Precipitate Phases
Fine precipitates are distributed throughout the matrix. These precipitates strengthen the alloy through precipitation hardening.
Common precipitates include:
Mg2Si in 6061-T6.
Al2CuMg (S-phase) and MgZn2 (η-phase) in 7075-T6.
These fine, dispersed particles hinder dislocation movement, improving strength.
3. Grain Structure
The grains are typically equiaxed (roughly equal in dimensions) after heat treatment and quenching.
Grain size affects the mechanical properties: smaller grains improve strength (Hall-Petch relationship).
4. Quenched-In Dislocations
After quenching, a high density of dislocations may be retained within the microstructure, which contributes to strength during aging.
5. Second-Phase Particles
Coarser secondary phases may exist, such as intermetallic compounds (e.g., FeAl3 or Mg2Si), depending on the alloy composition and heat treatment.
These particles are less desirable for mechanical properties but are remnants from the solidification process.
6. Artificial Aging Effects
During the aging process, the precipitates grow and coarsen, reaching an optimal size and distribution for maximum hardness and strength.
Observational Techniques
Optical Microscopy (OM): Reveals grain boundaries and larger particles.
Scanning Electron Microscopy (SEM): Shows fine precipitates and surface features.

Transmission Electron Microscopy (TEM): Provides high-resolution images of precipitate morphology and distribution.

The microstructure of T6-treated aluminum is engineered to balance strength, ductility, and corrosion resistance, making it ideal for applications in aerospace, automotive, and structural industries.

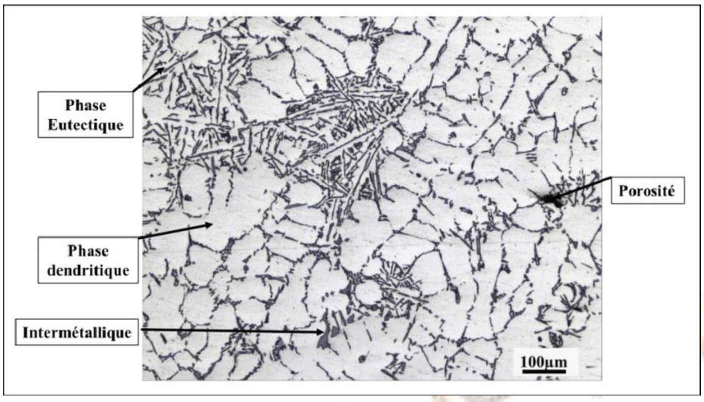


Fig 2 (a) Microstructure of old T6 specimen

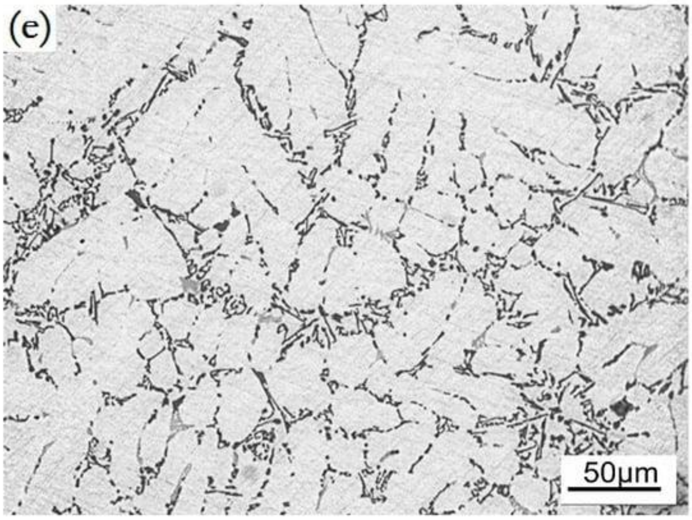


Fig 2 (b) Microstructure of new T6 specimen

IV. CONCLUSION-

Conclusion on Optimized Process Parameters for T6 Treatment on Aluminum

The optimization of process parameters for T6 treatment in aluminum alloys has demonstrated significant improvements in mechanical performance and microstructural refinement. Key conclusions derived from this study are as follows:

1. Solution Treatment Temperature and Time: Optimizing the solution treatment temperature ensures the dissolution of alloying elements into the matrix, while precise control of treatment duration minimizes over burning and grain coarsening. For the studied alloy, an optimal solution treatment range was found to balance solubility and structural stability.

2. Quenching Rate: Rapid quenching following solution treatment effectively suppresses undesirable phase formations, such as coarse precipitates, and retains a supersaturated solid solution. The optimized quenching rate ensures a uniform microstructure, which contributes to improved tensile strength and ductility.

3. Aging Parameters (Time and Temperature): Controlled artificial aging conditions result in the formation of fine, evenly distributed precipitates that maximize the alloy's yield strength and hardness. An optimal aging temperature and duration were identified to achieve peak strength without compromising toughness.

4. Microstructural Uniformity: The optimized process parameters enhance microstructural homogeneity, reducing defects such as porosity and grain boundary segregation. This contributes to superior fatigue performance and longer service life in dynamic applications.

5. Tailored Performance for Applications: The optimized T6 process parameters provide a balance between strength, corrosion resistance, and machinability, making the treated aluminum alloy suitable for applications in aerospace, automotive, and structural industries.

6. The optimization of process parameters did not have a significant impact on the metallurgical and mechanical properties of Al and its alloys; the final results observed were well refined and consistent.

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