

COMPUTER SIMULATION OF HEAT TREATMENT PROCESS FOR ALUMINIUM ALLOY

Temperature of aluminium alloy is simulated using MATLAB programming language for annealing, soaking to have uniformity of microstructure and quenching treatment processes. Workpiece selected for the study was aluminum alloy 6061-O, T1, T4 and T6 of different shapes: plate, cylindrical, rectangular, cubic and spherical aluminum alloy. The simulation identified the following properties: geometry (size), thermal conductivity, density, load pattern or shape which determine possibility of good heat treatment. Temperature of treated specimen were analysed using Finite Difference Method. At annealing temperature of 409.5 °C, fracture resistance of 670.5MPa and ultimate tensile strength value 298 MPa were achieved with 4% of ductility. Holding this temperature of 409.5 °C was necessary for achieving uniform microstructure at about 600 seconds which later quenched in water for 799 seconds to room temperature of 28 °C. Therefore the aluminum has equivalent length (thickness) treated of 25mm in plate section. The workpiece in the study increases in strength with increase in temperature for annealing therefore increases in thermal conductivity of the specimen was experienced. However, heat treatment in plate section of aluminium (6061-O) was faster in comparing to rectangular and cylindrical surfaces. Heat transfer coefficient was 1384W/m²K in plate and 692 W/m²K in cylindrical specimen of Biot number 0.2. The heat treatment processing was completed after 2256 seconds and aluminium 6061-O is more easily heat treatable to aluminium 6061- (T1, T4, T6) under the same condition. However, annealing of aluminium 6061 would negate effect of cold working at strain of 0.002 with yield strength of 149 MPa at ductility of 0.2%.

CHAPTER ONE

1.0

INTRODUCTION

1.1 Background of the Study

Planning and scheduling could be explained as a process that involves taking decision which is mostly used on a continuous basis in manufacturing and service industries. These kinds of decision-making play a vital role in production and procurement, in distribution and transportation, and in communication and information processing and among others (Pinedo, Glynn, *et al.*, 2005).

In heat treatment planning process, decision making method which tends to improves Aluminium Alloy samples of geometry functionability is very necessary. Basically, this process is usually used to alter the physical, and sometimes chemical, properties of the material. Also heat treatments could be used for the production with several related materials, such as glass. The process heat treatment entails heating of material to high temperatures, to obtain a desirable outcome such as softening or hardening of the material. The methods used in carrying out the process include case hardening, precipitation strengthening, annealing, tempering and quenching. Therefore heat treatment deals with condition in which heating and cooling are carried out for a particular reason of changing the properties of materials. However, the process of heating and cooling are sometimes form incidentally in the manufacturing processes which includes welding or hot forming. These processes is usually considerably practice to obtain increasing the strength of material, improve machining, and induces formability and restoring ductility with respect to cold working operation. Heat treatment has contributed immensely to manufacturing industries by improving the quality and the mechanical properties of materials which are to be manufactured.

1.2 Justification and Significance of the Study

Heat treatment is usually carried out to strengthen workpiece and also to improve manufacturability function during forming or machining. The quality of heat treatment for aluminium alloy workpiece depends on mechanical property and furnace temperature. It is good to determine the heating history and temperature distributions at different point in furnace and in workpiece. This will definitely improved the material loading design and temperature control. Unfortunately, there is presently no elaborate technique in place to simulate the process of heat-treatment. The present practice in heat treating industry ensures quality by experimental methods by measuring the temperature distribution in the furnace space or on the material surfaces.

Heat treating processes have faced difficulties in measuring temperature differences of a workpiece temperature because most methods available were indirect.

From the outside to the interior of the workpiece, the temperature is usually varied with respect to time and location. However, thermocouple is usually used to measured workpiece temperature which is set on the workpiece surface at selected points while the temperature inside the workpiece is unknown. Here, to obtain homogenous temperature distribution, a delay in time is very important in which through conduction that will be achieved. The major challenge is that there is no analytical model established for the time factor which is basically based on experience. With this constrain in either cases (wheather time is relatively too short or too long), it will have effect on the heat treated product, thus affect the functionality of the product. Also, there is no analytical model that could be used in determine the loading design of aluminium alloy workpiece. This made it difficult to establish an optimisation of the material loading due to non uniformity of temperature distribution experience in the workpiece. The need to developed AAW mathematical model for heat transfer in the process cannot be over

emphasized. This could be achieved and modelled using the principle of conduction as well as finite difference method for predicting temperature history of AAW.

Aluminium alloy workpiece could be used to heat treatment relieve internal stresses, to improve machinability and thus reduce brittleness. The mechanical Properties of AAW which includes toughness, hardness, strength, wear resistance, etc can be altered to achieve particular applications. Generally, the fundamental principle of heat treatment of AAW is the process of heating and cooling thereof.

Heating and slowly cooling will relieve internal stresses in most materials. Therefore, the underlying micro-structural changes induced in materials during heat treatment are complex. In the aerospace industry, heat treatment is usually performed after welding or forming (Alberg, 2003).

The use of computer program to simulate and predict temperature history of AAW during heat treatment would help to predict functionability of the material in a given time at optimised cost.

1.3 Aim and Objectives of the Study

Aim

This study aimed at developing a computer program for predicting temperature history during heat treatment of AAW. The objectives of the study include to:

Objectives

- i. predict annealing temperature
- ii. predict soaking temperature
- iii. predict quenching temperature
- iv. investigate the rate of heat transfer in the workpiece using Biot number
- v. investigate the hardness of the material

1.4 Scope of this Study

This study is model and simulates heat treatment cycle consisting of annealing process, soaking (holding) and quenching (cooling) that may be used for Aluminium alloy samples of various geometrical sizes. The model makes use of finite difference method to numerically distribute the temperature profile in the workpiece. Similarly Brinell hardness test was conducted experimentally to validate the obtained result.

2.0

LITERATURE REVIEW

2.1 Basic Principles of Heat Treatment

Heat treatment of a non ferrous metal or its alloy is simply the sequential procedure which involves the controlled heating and cooling operations, carried out for the purpose of altering its alloy and the microstructure to achieve required properties (Kopeliovich, 2009). Hardening and annealing are the two common processes of heat treatment.

2.1.1 Alloying Elements in Aluminium

The alloying elements commonly used in heat treatment of aluminium alloys include manganese, silicon, magnesium, copper and sometimes, nickel, titanium, zinc, and chromium. The overall effect of alloy additions was to raise the yield strength, hardness and tensile strength, with corresponding reduction in percentage elongation. Here, the alloying elements are added extensively in aluminium castings to raises the quality of casting as well as its mechanical properties. In general, for the 6000 series of heat treatable alloys of aluminium are applied in a wide range of products, largely as extruded shapes, the principal applications of the 2000 and 7000 series alloys are in the aircraft and aerospace industries. Modest inroads are being made by titanium alloys, beryllium and composite materials, but aluminium is still the principal structural material in both aircraft and missiles. Even in the new giant transport and passenger planes, as well as the supersonic Concorde, designers working with materials engineers have chosen aluminium as the major structural material.

2.2 Precipitation Hardening of Aluminium Alloy

Precipitation Hardening are usually been used to strengthen, magnesium alloys, nickel-base super alloys, aluminium alloys beryllium-copper alloys, and precipitation- hardening stainless steels. Here, the aluminium alloy is heated to an extreme temperature which in turn would allow an appreciable quantity of the alloying element into solid solution. This will then quickly quenched to room temperature, then its trapped the alloying elements in solution. On reheating to an intermediate temperature, the original metal rejects the alloying element which is in form of fine precipitates which thus, produce matrix strains on the lattice. These particles fine precipitate serves as resistant to the dislocations movement and provide resistance to slip, which allows hardness and strength to improve.

2.2.1 Particle Hardening

Particle, or dispersion, hardening occurs when extremely small particles are dispersed throughout the matrix. If a dislocation has a fine particle, it will either be cut through the particle or bow (loop) on it, as shown in fig 2.1.

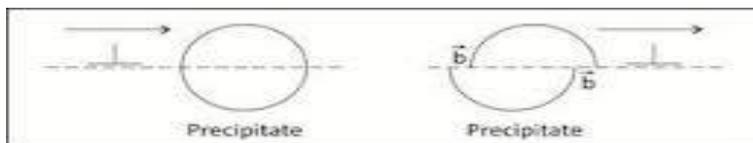
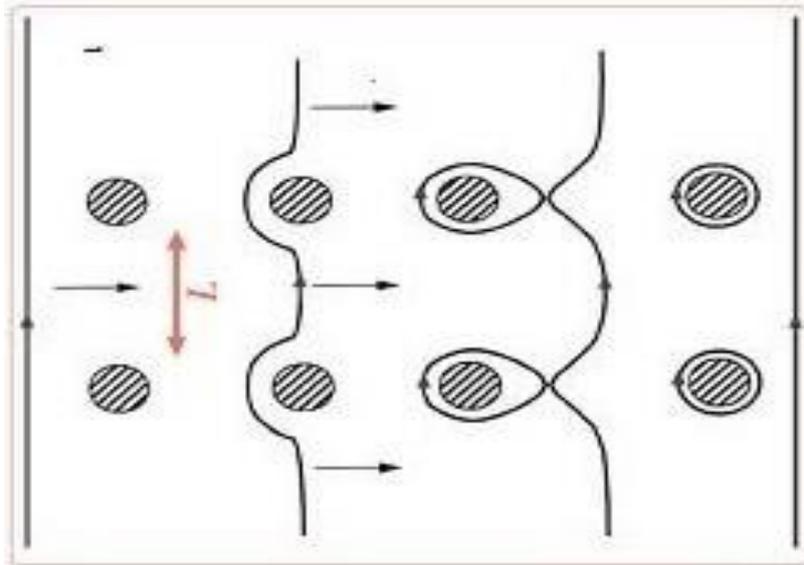


Figure 2.1a Dislocation shearing through particle



Dislocation looping Around Particles

Figure 2.1b Particle strengthening

Strengthening with the precipitation hardening plays a vital role to obtain a high-strength aluminium alloy. The stages involves in precipitation hardening are as follows:

- (a) 1st stage - Solution heat treating
- (b) 2nd stage - Rapid quenching
- (c) 3rd stage - Aging

2.2.2 Solution Heat Treating

In solution heat treating, the alloy is heated to a temperature that is extreme to obtain soluble solution alloying elements. Considering the alloy is soaking for a sufficient time to achieve a nearly homogeneous solid solution. The time at temperature required for solution treating should be long enough for diffusion to occur to produce a solid solution (supersaturated).

Quenching

During quenching, the important factor is for the alloy to be quickly enough so that the supersaturated solid solution is maintained on cooling to room temperature. On the other hand, rapid quenching often results in high residual stresses and part distortion, so less drastic quenches frequently are used with some sacrifice in properties to minimize distortion.

To avoid appreciable precipitation during the quenching process, there are two conditions that should be considered: (1) the period needed to transfer the part from the inner furnace to the quench medium which should be relatively short to preclude slow cooling as very rapid precipitation can occur easily.

(2) For the cooling rate capacity of the quench medium must be such that little or no precipitation occurs during cooling. For example, if a quench tank is used, the tank must be large enough that there is not a significant rise in the tank temperature during quenching. Aluminium alloy parts are usually tank quenched in cold water to provide the optimum strength and corrosion resistance.

(3) Aging

This is the final stage in the precipitation hardening. Hardening is achieved by aging at room temperature. This is otherwise known as natural or artificial aging. In some cases, sufficient precipitation could be achieved in a few which yield stable products with appropriate properties for different applications. However it could be artificially aged, which tends to increase the strength and hardness in cast and wrought products. The other alloys with behaviour of slow precipitation reactions at room temperature are usually artificially aged.

2.2.3 Effect of Annealing on Cold Worked Metals

Heating of a cold worked metal to a high enough temperature eliminates by diffusion, most of the crystal defects and restores the properties to their original value. Such a heat treatment is referred to as annealing. During annealing, cold worked metals undergo the restoration processes of recovery and recrystallization.

Recovery is simply the process of releasing internal stresses in a workpiece at relatively lower temperature, above $0.1T_m$, where T_m is defined as the melting point considering the absolute temperature scale. During these processes, relaxation of internal stresses and redistribution of more mobile dislocations occur, known as polygonization. Recovery although releases the internal stresses, it hardly affects the mechanical properties as shown in figure 2.2. This is an important method for reducing the internal stress in castings, forgings, welded joints, without lowering the strength acquired during cold working. Another name for this is stress-relief annealing.

FIGURE 6.47 Effect of annealing on the structure and mechanical property changes of a cold-worked metal. (Adapted from Z. D. Jostzelski, "The Nature and Properties of Engineering Materials," 2d ed., Wiley, 1976, p. 228.)

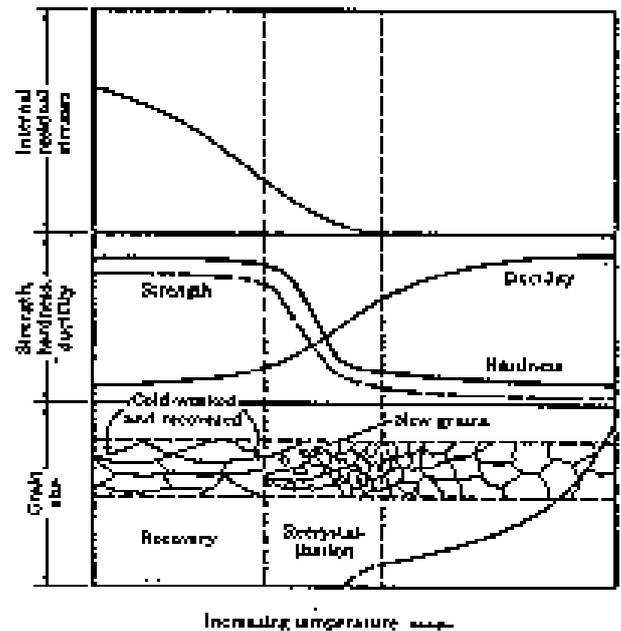


Fig. 2.2 Effect of Annealing on Cold Worked Metal

The treatment of alloys for precipitation hardening requires very careful control, because in most instances the temperature at which the homogeneous solid solution is attainable lies within a very narrow range. Heating above this temperature may result in burning, embrittlement, or actual fusion. Too low a temperature, on the other hand, will permit the complete separation of a portion of the second phase in the grain boundaries, thus preventing the attainment of maximum hardening. Proper time must be allowed for complete homogenization at the proper temperature. In some alloys, such as nickel-silicon and iron-copper, etc, precipitation does not occur very rapidly; hence, air cooling may be sufficiently rapid so that maximum hardening can be attained later by artificial aging.

The combination of aging temperature and aging time, known as the precipitation treatment, is rather critical for some alloys. As a general rule, a decrease of the aging temperature

requires a considerable increase of the time of aging. In some alloys, lower aging temperature brings about appreciable increase in strength without materially decreasing the ductility. This is evident in some aluminium-copper alloys.

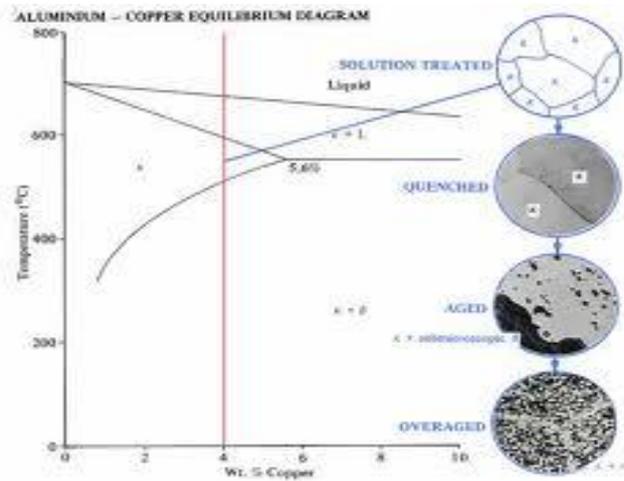


Fig 2.3 Structures produced in different treatments of precipitation-hardening alloys

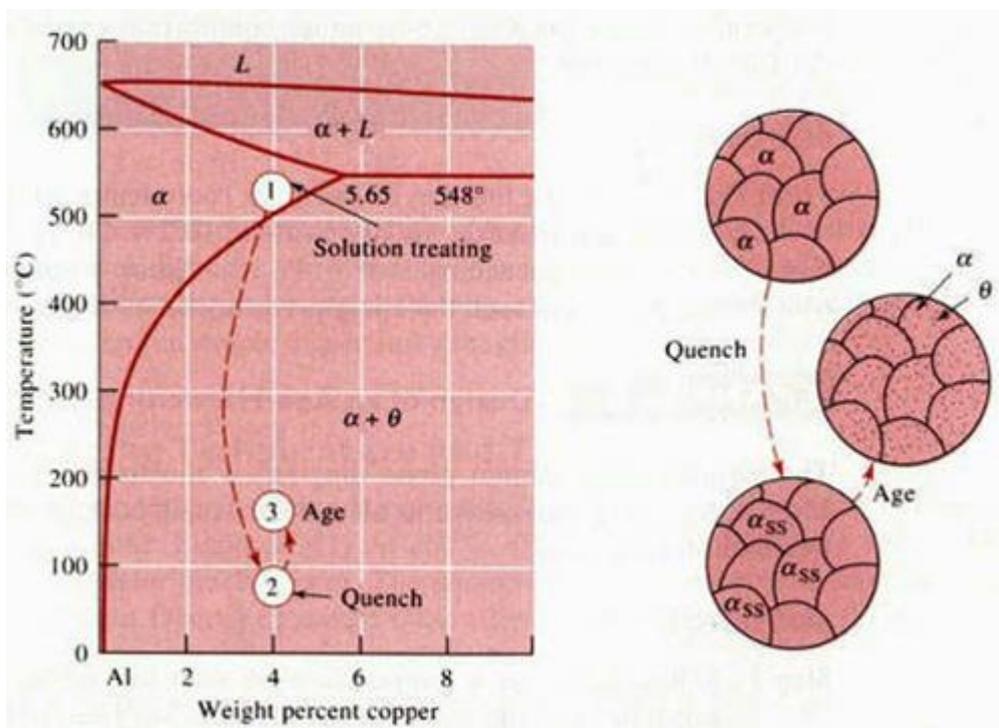


Fig.2.4 The Al-Cu phase diagram indicating the aluminium rich end with the stages in the age-hardening and microstructures that are formed.

2.2.3 Designates Tempers of Aluminium Heat Treatable Alloys

W- This is solution heat treated: this occurs after solution heat treatment at which an unstable temper alloys is formed.

T- This thermally treated to produce stable tempers other than F, O or H: This T is usually followed by numerical digits which indicate one specific form of basic treatments as stated below:

T1- This is partially solution heat-treated that was naturally aged to a substantially stable condition:

T2- This is annealed (cast products only): This tends to improve dimensional stability.

T3- This is solution heat treated which is then cold worked: This T3 is applies to products cold worked to improve strength.

T4- This is solution heat treated, hence naturally aged to a appreciable stable condition:

T5- This is Partially Solution Heat Treated and Artificially Aged:

T6- This is Solution Heat Treated and Artificially Aged:

T7- This is solution heat treated and stabilized.

T8- Means solution heat treated, then Cold Worked, and Artificially Aged.

T9- This is solution heat treated, which was artificially aged, and cold worked.

T10- This is partially solution heat treated, that was artificially aged, and cold worked.

2.2.4 Aluminium-Copper Equilibrium Diagram

When metals are alloyed, they have a tendency to enter into solution, as salt enters into solution when placed in water; and as with a salt and water solution, the higher the temperature of a material, the higher the amount of added constituent will be taken into solution before the saturation point is reached. Again, like salt and water, a super-saturated metallic solution, on slow cooling, drops out or precipitates the excess substance that was absorbed at the higher temperature.

2.3 The Stages of Heat Treatment

Heat treatment is accomplished in three major considered stages:

- i. Heating the metal workpiece slowly to obtain a homogenous temperature distribution throughout the workpiece
- ii. Soaking the metal at a specific temperature for a desirable period
- iii. Finally, Cooling the metal to room temperature to achieved the desired result

2.4 Guinier Preston Zone

The essential criteria for precipitation hardening alloy system are that the solid solubility boundary limit will decrease with reduction in temperature. The diagram i fig. 2.1 for the Al-Cu illustrated it clearly.

Guinier Preston Zone: In 1938, Guinier Preston independently concluded from x-ray attraction investigations that the minute aggregates of solute atoms founded within the supersaturated solvent. These aggregates are known as Guinier Preston Zones. The actual precipitated which is nucleated from G.P zone stage and grow to a complete particle which is microscopically

recognizable. In this state, however, the maximum strength has been pushed and the alloys is on an over aged state.

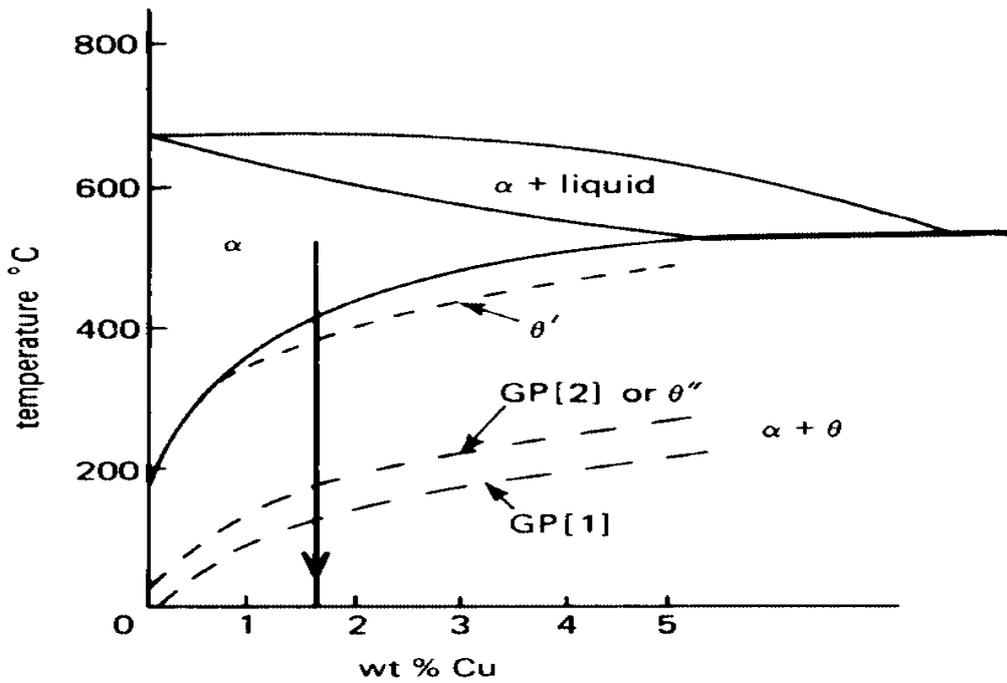


Figure 2.5: Binary diagram of Al–Cu indicating GP [1]

Source: Smallman and Bishop, (1999).

Where:

GP [1] is Guinier-Preston 1 zones (G-P1 zones)

GP [2] is Guinier-Preston 2 zones (G-P2 zones)

Wt % is percent weight

θ'' And θ' phases represent solvus lines (dotted)

Considering heat-treatment stages for precipitation-hardening, the aluminium alloy in solution heat treatment firstly at heat treated elevated temperature and thus rapidly quenching in water. The effect of this rapid cooling is to suppresses the separation of the θ –phase while the alloy tends to exists at the low temperature in an unstable supersaturated state. However, after quenching, the alloy is allowed to ‘age’ for an appreciable period of time, the second phase precipitates out completely. Then precipitation would form by a nucleation and growth processes, fluctuations in solute concentration provides very small clusters of atoms in the lattice. This act as nuclei for the precipitate (reinforced) (Smallman and Bishop, 1999).

Also, the size of the precipitate tends to be finer when the degree of heat became lowered, and hardening of the alloy is associated with a critical dispersion of the precipitate. At any recognise given temperature, ageing is permitted to proceed too far, coarsening of the particles occurs. At this stage, the alloy will be softer, and this becomes over-aged condition (Smallman and Bishop, 1999).

Therefore, in supersaturated solid solution, precipitation formed in sequential stages:

- i. The formation of plane cluster known as Guinier-Preston1 zones (G-P1 zones) by Segregation of Cu atoms.
- ii. Diffusion of Cu atoms via G-P1 zones and hence forms what is called GP2 zones or θ'' phase. This θ'' phase is always coherent with the matrix.
- iii. Formation of θ' phase. The phase is partially coherent with the matrix as it provides adequate hardening.

2.4.2 Al–Si alloys

Hardening of aluminium-silicon alloys is different compare to standard phase diagram as aluminium does not have solid solubility in silicon at any given temperature (Fontecchio, 2002). However, the phase is usually replaced by pure silicon only as there is no beta phase. This is shown in Figure 2.6.

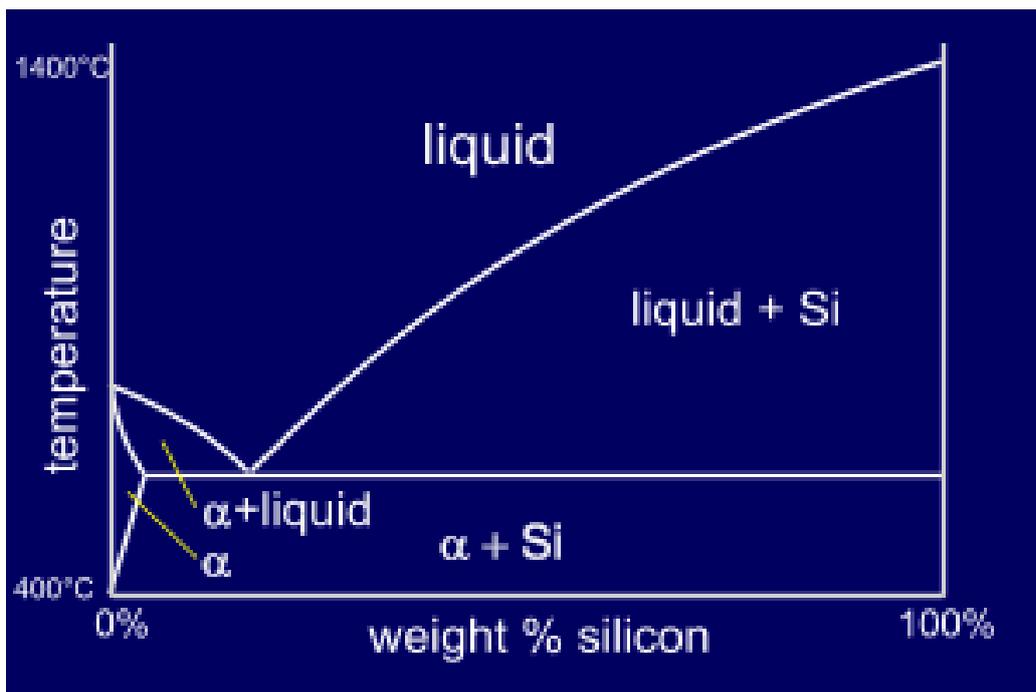


Figure 2.6: Al–Si Phase diagram (Fontecchio, 2002).

2.5 Simulation of heat treatment

Heat treatment is an extremely desirable sequence in the production of aluminium alloy products, and this is useful in controlling the mechanical properties such as hardness, toughness, dynamic strength and metallurgical structure of a component. However, heat treatment process can easily be accompanied with undesired effects like poor toughness, low strength, component distortion etc, as this could leads to crack formation. Therefore, effectiveness or failure of heat treatment will eventually determine the product reliability. For

any design and development, heat treatment must be taken into consideration in the manufacturing process.

2.5.1 Simulation of the based design

The simulation-based design is necessary to resolve and analyse the effects of heat treatment in arrears in order to achieve optimize by varying the related materials and the shape of the workpiece. As the part shape is designed, it is very indispensable to ascertain that this process is correctly done according to specification and hence process window is secure against process parameter variables. Considering finite element analysis software (SYSWELD), the calculations could be done for all heat treatment processes, while an appreciable physical effect is considered (Boitout *et al.*, 2011). Therefore, the part designer could influence manufacturing costs minimally and thus, optimizing product reliability and quality (Boitout *et al.*, 2011).

2.5.2 Software and Applications

Part designers and dedicated solutions can easily be achieved. Therefore heat treatment focuses on the appropriate procedures of this process heat treatment and needed response to challenges immediately. Dedicated solutions that fit the requirement in the heat treatment job shop are available. These heat treatment practitioners usually focus on efforts to evaluate the effective balance of cost, geometrical shape, material, and process heat treatment that can be involved.

2.6 Modeling of Heat Treatment

2.6.1 Material Modeling for Simulation of Heat Treatment

According to Alberg (2003), heat treatment could cause undesired stresses and deformations. This condition needs to be considered while designing or altering the procedure of manufacturing over a particular part. Considering the former activities could assist, however it's cost effective and time consuming experimental analysis which is usually essential to assess, material selection, design of part and scheduling of manufacturing. The best way to reduce cost and time in development of product can be used in simulating tools that could suggest the properties and shape of a component caused by using a better process in manufacturing. A reduction in cost implication and good knowledge of final properties already known about the product developmental stage can give an organization/company a better market share and competitiveness thereof.

Objective of heat treatment simulation studies is to:

- i. Establish a predictive theory that would favour the prediction of residual stresses, distortion, and material properties such as microstructure of material and hardness after a heat treatment process.
- ii. Improve heat treatment process and it is important to understand the material behaviour that controls the process parameters.

One frequently used numerical method to simulate thermo-mechanical behaviour is the finite element method which was normally been used to the thermo-mechanical manufacturing processes such as welding (Hibbit, and Marcal 1973; Ueda and Yamakawa, 1971). Simulation of heat treatment has also been made since the 1970's. Early heat treatment simulations were carried out (Burnett and Pedovan, 1979). Burnett and Pedovan (1979), calculated residual stresses in case-hardened cylinders. Sjöström (1982) also calculated quench stresses in

aluminium alloy. Rammerstorfer et al. (1981) made simulation of the heat treatment process, which included creep and phase changes. During the last two decades, most of the heat treatment simulations have been made to solve quenching problems. The primary intent with these simulations has been to predict distortion and residual stresses. Thuvander (1996) considered simulation of distortion as a result of quenching. Simulation tools have also been developed to calculate hardness after quenching (Tajima, 1996). Simulation combining quenching and tempering have also been carried-out (Ju et al., 1996). Simulations of stress relief heat treatment are less common. Josefson (1982) numerically analyse of the residual stresses after a stress relief heat treatment of workpiece (A thin wall pipe). Nevertheless, combined simulation has been performed by Josefson (1982), that is been calculated after the heat treatment of a thin wall pipe (post weld). Wang and Murakawa (1998) .

2.7 Aluminium Solution Heat Treatment

A most common heat treatable alloy is Al/Cu alloys. This Al/Cu alloys are heated above a critical temperature, the *Cu* in the alloy will goes into “Solid Solution”. It will remains at this temperature long enough for the thickness of material all of the *Cu* will have gone into solution. Considering this point, the alloy is soft and malleable, and at this state the alloy will, over the period of time, undergo a precipitation of the solid solution (natural aging). Some alloys require 4 to 5 days to attain most desirable properties.

Some other processes of heat treatment of aluminium alloy are (KeithCompany.com, 2012):

- i. The Solution Heat Treatment has variable factors such as:
 - a) Temperature
 - b) Time
 - c) The Load temperature uniformity
- ii. Quench with variable factors such as:

- a) considering speed when transferring workpiece from furnace to quench tank
 - b) Selection of Quenching media: water, polymers, water/polymer mixtures
 - c) Temperature of quenching media
 - d) Temperature of quenching media uniformity
 - e) Determine rise in temperature of quenching media during quench
- iii. Aging processes (variable factors such as):
- a) Temperature
 - b) Time
 - c) Temperature uniformity for loading

The essence of solution heat treatment in aluminium workpiece is to achieve the maximum concentration of hardened solute, such as copper, zinc and magnesium in solution by heating the alloy to a temperature to form a single phase. This will allow the solute atoms of a two phase to dissolve back into solution and hence produce a single phase in equilibrium.

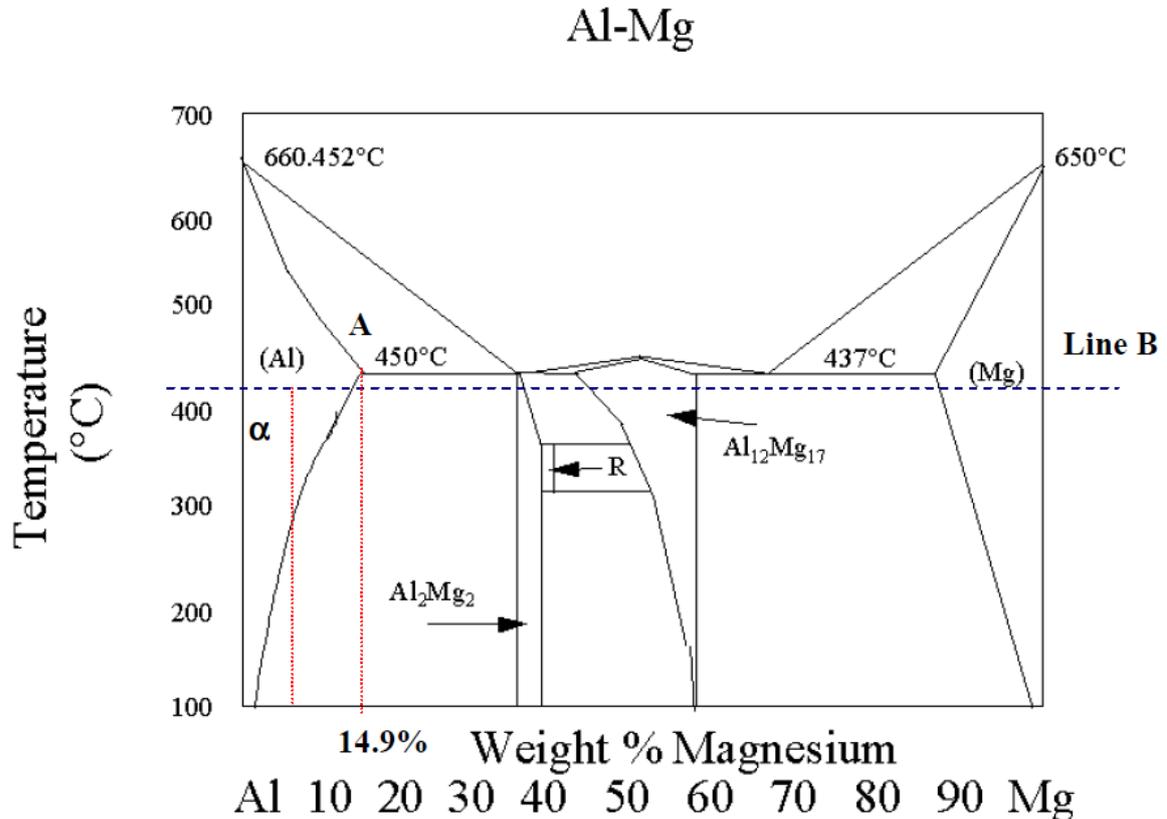


Figure 2.7: Aluminium-Magnesium Phase Diagram (Source, Fontecchio, 2002).

In order to achieve this, the aluminium alloy must be heated firstly into the α range of the diagram. While doing that, the β phase dissolves again into solution as the alloy becomes a homogeneous solution of *the two elements (Al & Mg)*. Basically, the solutionizing temperature is dependent of the solute analysis (concentrate); this implies, the temperature is same regardless of initial amount of Mg concentrate in the system. For most commercial applications, considering the solution heat treating temperature is usually below the eutectic temperature (see line B on the phase diagram as shown in fig. 2.7).

2.8 Quenching Media

The usual quenching media for aluminium alloys are oil, water and polymer solutions. These media varies in the rate at which they give off the heat out of a quenched part. This quenching process involves cooling a material to varies lower temperature i.e. cooling (quenching) the particular part by immerse in oil or water or by forced gas or air. If the specified part is heated near its melting temperature, the alloying constituents are usually in solution, quenching the part rapidly as its serve to envelop the alloys in a crystalline structure which in turn made it stronger than its original part. The resultant effect of rapid quenching causes the residual stresses and brittleness in a part. Therefore, to obtain the desired material property, it is necessary to control the rate of cooling of the part (Bylund *et al*, 2008).

The cooling rate of a material is governed by the heat transfer coefficient, which is a function of heat flux and temperature gradient. This statement can be found experimentally (for small geometries), by equation (2.1) (Bylund *et al*, 2008):

$$h_c = \frac{-mC_p T}{A(T-T_{air})} \cdot \frac{dT}{dt} \quad (2.1)$$

Where:

h_c = Average HTC considering the surface of the material

m = Mass

C_p = Specific heat;

T = The Temperature T, for a given time of the material;

T_{air} = Temperature of air;

A = Surface area on that material

CHAPTER THREE

3.0 MATERIAL, EQUIPMENT AND METHOD

3.1 MATERIALS AND EQUIPMENT

The following materials are required for the heat treatment in forming/machining processes.

EQUIPMENT

3.1.1 Furnace Specification

The furnace requires in the heat treatment electric furnaces. The furnace in the study is Cress Single Chamber Annealing Furnace. It has capacity of 1000kg of charge with power rating of 48kW and temperature ranges of 1100 to 3000 °C. The furnace model C1228.DW with internal exhaust fan of 1.4630 m³.



Figure 3.1: Cress single Chamber Annealing Furnace (SEDI, 2011).

MATERIALS

3.1.2 Workpiece

Workpiece (aluminium alloy) and this depend on the following factors:

- a) ' A ' or ' V ' = Geometry size (area or volume)
- b) λ = Thermal conductivity
- c) ρ = Density
- d) γ = Load pattern or shape
- e) C_p = Specific heat capacity
- f) Composition of the workpiece is indicated in Table 3.1.

Table 3.1: Aluminium Alloy 6061 Composition (ASTM-B209)

Aluminium alloy 6061 Component	Weight %
Percentage of Aluminium	96.20
Percentage of Magnesium	1.20
Percentage of Silicon	0.75
Percentage of Iron	0.70
Percentage of Copper	0.40
Percentage of Zinc	0.25
Percentage of Titanium	0.16
Percentage of Manganese	0.14
Percentage of Chromium	0.20

Source: SEDI, 2011.

Table 3.2: Specification for Aluminium 6061 (ASTM-B209)

Specification	Unit
Elasticity Modulus (GPa)	70
Density (kg/m ³)	2700
Thermal conductivity (W/mK)	173
Melting Temperature (°C)	585
Poisson Ratio (ν)	0.33

Tensile strength (O, T1, T4, T6) MPa	125,160, 207, 310
Yield strength (O, T1, T4, T6) MPa	55, 85, 110, 275
0.2% Proof strength (O, T1, T4, T6) MPa	100,150, 190, 240

Source: (ASTM-B209, 2010)

3.1.3 Computer Simulation Furnace Specification

32 byte personal's computer for running standalone application of MATLAB version 2009b.

3.2 Methods

Heat is transferred in the process by three different modes such as, conduction, convection and radiation or a combination of these three modes.

3.2.1 Conduction

Conduction is a flow of heat within an object in response to a temperature difference. It is experience in a static heat process medium which is usually occurring in solids. However conduction may exist in other state to some extent (gases and liquids). This is governed by Fourier's principle as it states that considering the length of path of the heat flow, the rate at which heat is flow in a simple homogeneous solid is directly proportional to the area of the

section at right angles in the direction of heat flow, and to temperature difference. This could be expressed mathematically as given by equation (3.1), (Bejan and Kraus, 2003):

$$q \propto A \left(\frac{dT}{L} \right) \quad (3.1)$$

$$q_{cond} = -\lambda A \left(\frac{dT}{L} \right) \quad (3.2)$$

Where:

q_{cond} = considering heat that are flow in an object per unit time (watt)

A = cross sectional surface area of the workpiece in m^2

dT = temperature gradient (faces of homogeneous solid of thickness “ dx ” at which heat flows, $^{\circ}C$)

L = the body thickness with respect to the direction of flow, m

λ = for the thermal conductivity of the workpiece (W/mK)

3.2.1.2 Classification of Workpiece Shape

Biot (Bi) number simply defines as the ratio of the heat transfer coefficient of an outside body to conductive heat transfer coefficient inside the workpiece (Bejan and Kraus, 2003). $Bi =$

$$\frac{ht_{eff}}{\lambda} \quad \begin{cases} < 0.1 \text{ lumped} \\ \text{otherwise massive} \end{cases} \quad (3.3)$$

$$h = h_{conduction} + h_{convection} + h_{radiation} \quad (3.4)$$

$$\text{Plate, } t_{eff} = V/A \quad (3.5)$$

$$\text{Cylinder or bar with rectangular section, } t_{eff} = 2V/A \quad (3.6)$$

Spherical object, $t_{eff} = 3V/A$ (3.7)

Cubic object, $t_{eff} = 3V/A$ (3.8)

Where:

h = Heat transfer coefficient or heat flux in W/m^2K

t_{eff} = equivalent thickness of the workpiece in m

V = workpiece volume in m^3

A = workpiece surface area in m^2

3.2.2 Convection

Convection can be explained as a technique of heat transfer in the actual movement of heated molecules which is by a freestanding unit (Bejan and Kraus, 2003). This analysis is adopted for quenching process. The convection heat transfer is generally governed by Newton's law of cooling and given by (Bejan and Kraus, 2003):

$$q_{conv} = h_{convection} A (t_s - t_f) \quad (3.9)$$

Where:

$h_{convection}$ = considering the convective heat transfer coefficient in W/m²K

t_s = the temperature of the surface of the material in °C

t_f = fluid temperature in °C

Convective heat transfer coefficient (h) is given by Nusselt factors if it were quenched by air or gas medium (Bejan and Kraus, 2003). Nusselt Number (Nu) represents a dimensionless heat transfer from a fluid flow through a specified boundary surface (Lindberg, 1994):

$$Nu = h_{convection} \left(\frac{L}{\alpha_f} \right) \quad (3.10)$$

Where:

Nu = Nusselt Number

L = Characteristic length in m

α_f = fluid thermal conductivity in W/mK

3.2.3 Radiation

According to Bejan and Kraus (2003), equation (3.11) is required for radiative in transferring of heat within a surface and its surrounding in Watt and it is given by:

$$q_{rad} = \epsilon \sigma A (T_s^4 - T_{sur}^4) \quad (3.11)$$

Where:

ϵ = Emissivity (considering the geometry and surface properties)

σ = Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$

T_s = Surface temperature in °C

T_{sur} = Surrounding temperature in °C

3.2.4 Furnace Temperature

According to Vader (2002), for all types of furnaces, the average furnace temperature T_{fur} at time t is given by:

$$T_{fur(t+1)} = T_{fur(t)} + Q_{s(t)}\Delta t/c_{fur} \quad (3.12)$$

Where:

$T_{fur(t)}$ = average temperature of the furnace with respect to time (t) in °C

$T_{fur(t+1)}$ = average temperature of the furnace with respect to time (t+1) in °C

$Q_{s(t)}$ = heat storage in heat treating furnace in J/s

Δt = incremental time interval in second

c_{fur} = heat capacity of furnace in J/kgK

3.2.5 Temperature Distribution of Workpiece

Material/workpiece temperature depends on material characteristics, thermal conductivity, heat transfer by radiation and convection during heat treatment (Kiusalaas, 2005). In this process the workpiece is subjected to heat transfer media of convection and radiation. Therefore temperature in this region is distributed and thus calculated using Finite Difference Method as follows:

Let energy (E_H) required in Joules for heat treatment process equals:

$$E_H = E_{conv} + E_{rad} \quad (3.13)$$

$$E_{conv} = hA(T_{av} - T_{mat}) \quad (3.14)$$

$$E_{rad} = \varepsilon\sigma A(T_{heater} - T_{mat}) \quad (3.15)$$

The heat stored in the workpiece is given by equation (3.16):

$$E_H = \rho cVdT/dt \quad (3.16)$$

Substituting equations (3.14-3.16) for the equation (3.13) we have:

$$\rho CVdT/dt = hA(T_{av} - T_{mat}) + \varepsilon\sigma AF(T_{heater}^4 - T_{mat}^4) \quad (3.17)$$

$$dT/dt = \frac{hA(T_{av}-T_{mat})+\varepsilon\sigma AF(T_{heater}-T_{mat})}{\rho CV} \quad (3.18)$$

For a plate, volume is defined as

$$V = L_{eff} A \quad (3.19)$$

Then, Substituting the equation (3.19) into 3.18 we have:

$$dT/dt = \frac{hA(T_{av}-T_{mat})+\varepsilon\sigma AF(T_{heater}-T_{mat})}{\rho CL_{eff} A} \quad (3.20)$$

$$f(t) = \frac{hA(T_{av}-T_{mat})+\varepsilon\sigma AF(T_{heater}-T_{mat})}{\rho CL_{eff} A} \quad (3.21)$$

Where:

T_{mat} = workpiece temperature in °C

T_{av} = average furnace temperature in °C

ρ = density of workpiece in kg/m³

T_{heater} = heater temperature in °C

σ = Stefan-Boltzmann constant

C = specific heat capacity in J/kgK

The derivations of the finite difference approximations for the derivatives $f'(t)$ are based on forward and backward Taylor series expansions of $f(t)$ about *time* (t) such as (Kiusalaas, 2005):

$$f(t + h) = f(t) + hf'(t) + \frac{h^2}{2!}f''(t) + \frac{h^3}{3!}f'''(\theta) \quad (3.22)$$

$$f(t - h) = f(t) - hf'(t) + \frac{h^2}{2!}f''(t) - \frac{h^3}{3!}f'''(\theta) \quad (3.23)$$

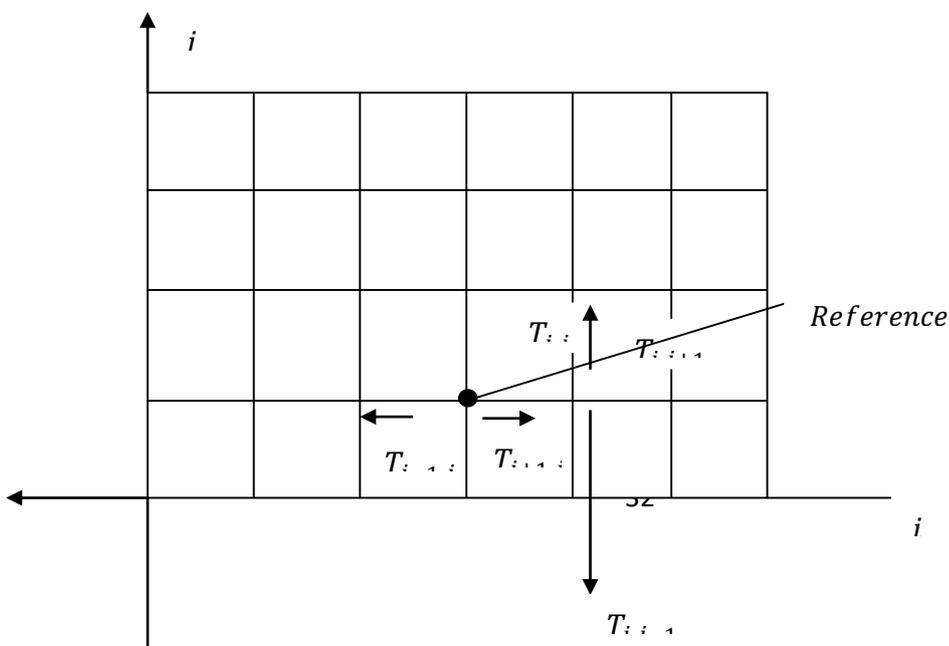


Figure 3.2: Finite Difference for Temperature Nodal Point

The sum of this series is given as:

$$f(t + h) + f(t - h) = 2 f(t) + h^2 f''(t) \quad (3.24)$$

By relating equation (3.24) to T in i and j direction with respect to Figure 3.2, then we have the following directions from reference point $(T_{i,j})$ in either square mesh or rectangular mesh as: $T_{i-1,j}$, $T_{i+1,j}$, $T_{i,j+1}$ and $T_{i,j-1}$.

Therefore sum in i direction is given as:

$$T_{i+1,j} = T_{i,j} + hf'(T_i)_{i,j} + \frac{h^2}{2!} f''(T_i)_{i,j} + \frac{h^3}{3!} f'''(T_i)_{i,j} \quad (3.25)$$

$$T_{i-1,j} = T_{i,j} - hf'(\theta_i)_{i,j} + \frac{h^2}{2!} f''(T_i)_{i,j} - \frac{h^3}{3!} f'''(T_i)_{i,j} \quad (3.26)$$

$$T_{i+1,j} + T_{i-1,j} = 2 T_{i,j} + h^2 f''(T_i)_{i,j} \quad (3.27)$$

And the sum in j direction is given as:

$$T_{i,j+1} = T_{i,j} + hf'(T_j)_{i,j} + \frac{h^2}{2!}f''(T_j)_{i,j} + \frac{h^3}{3!}f'''(T_j)_{i,j} \quad (3.28)$$

$$T_{i,j-1} = T_{i,j} - hf'(T_j)_{i,j} + \frac{h^2}{2!}f''(T_j)_{i,j} - \frac{h^3}{3!}f'''(T_j)_{i,j} \quad (3.29)$$

$$T_{i,j+1} + T_{i,j-1} = 2T_{i,j} + h^2f''(T_j)_{i,j} \quad (3.30)$$

Considering Laplace equation given by:

$$\nabla^2\theta = 0$$

$$\Rightarrow f''(T_i)_{i,j} + f''(T_j)_{i,j} = 0$$

Substituting the equations (3.26 and 3.30) into Laplace equation above as stated, therefore:

$$\frac{T_{i+1,j} + T_{i-1,j} - 2T_{i,j}}{h^2} + \frac{T_{i,j+1} + T_{i,j-1} - 2T_{i,j}}{h^2} = 0$$

For a square mesh $h = h$, and a rectangular mesh $h \neq h$, thus:

$$T_{i,j} = \frac{T_{i+1,j} + T_{i-1,j} + T_{i,j+1} + T_{i,j-1}}{4} \quad (3.31)$$

Equation (3.31) improves with over-relaxation formula with weighting factor λ , $1 < \lambda < 2$

$$(T_{i,j})_{overrelation\ for\ n\ time} = \lambda (T_{i,j})_n + (1 - \lambda) (T_{i,j})_{n-1} \quad (3.32)$$

The finite difference gives good numerical approximation (Kiusalaas, 2005 and Kreyszig, 2006).

This predicted temperature in equation (3.32) is melting temperature of the workpiece. The one-third of workpiece (pure metal) melting temperature (T_m) or one-seventh metal alloy

melting temperature are annealing temperature at this point the temperature is held for reasonable time and the procedure is called soaking.

Thus we have:

$$T_{i,j} \text{ annealing pure} = \frac{1}{3} (T_{i,j})_{\text{overrelation for n time}} \quad (3.33a)$$

$$T_{i,j} \text{ annealing alloy} = \frac{1}{7} (T_{i,j})_{\text{overrelation for n time}} \quad (3.33b)$$

$$T_{i,j} \text{ recrystallisation pure} = 0.3 (T_{i,j})_{\text{overrelation for n time}} \quad (3.34a)$$

$$T_{i,j} \text{ recrystallisation alloy} = 0.7 (T_{i,j})_{\text{overrelation for n time}} \quad (3.34b)$$

3.3 Annealing Treatment

Heat treatment by annealing procedure is achieved by recovery; recrystallisation and grain growth but in this study we consider the first and the second procedures. According to Callister.Jr (2001), the ability of material to absorb energy when as it's elastically deformed which upon unloading its energy recovered. This process is called resilience (Callister.Jr, 2001). It is measured in terms of Modulus of resilience, U_r the strain energy per unit volume been needed for a material to undergoes stress from an unloaded state up to point to achieve yielding and this can be expressed by (Callister.Jr, 2001):

$$U_r = \frac{\sigma_y^2}{2E} \quad (3.35)$$

Equation (3.35) is used to achieve recovery under annealing condition while equation (3.36) a strain or work hardening is adopted to calculate for recrystallisation for a situation under. Strain hardening is given by (Callister.Jr, 2001):

$$\%CW = \frac{A_o - A_d}{A_o} * 100 \quad (3.36a)$$

$$\%RA = \frac{A_o - A_d}{A_o} * 100 \quad (3.36b)$$

$$\%EL = \frac{l_f - l_o}{l_o} * 100 \quad (3.37)$$

Equation (3.36a) is defined as condition the whereby a ductile metal becomes stronger and harder with plastic deformation. Equation (3.37) is used to measure percentage elongation; this helps to determine ductility and equation (3.36b) serves to know area of reduction after machining or cold work (Callister.Jr, 2001).

Where:

U_r = resilience in J/m³

σ_y = Yield stress in N/m²

E = Young modulus in N/m²

$\%CW$ = percent cold work

$\%EL$ = percent elongation

$\%RA$ = percent reduction in area

A_o = original area in m²

A_d = area after deformation in m^2

l_f = final length after elongation in m

l_o = length of original workpiece in m

3.3.1 Annealing Working Stress

Upon reaching annealing temperature of equation (3.33) working stress is established as follows (Callister.Jr, 2001):

$$\sigma_w = \frac{\sigma_y}{N} \quad (3.37a)$$

$$\sigma_w = E\epsilon \quad (3.37b)$$

Where:

σ_w = working stress in N/m^2

σ_y = yield stress in N/m^2

N = Factor of safety

E = Young Modulus in N/m^2

ϵ = Strain

3.4 Soaking

The elastic property of isotropic material (no change in temperature) is achieved using the expression or the formula:

$$E = 2G(1 + \nu) \quad (3.38)$$

Where:

E = Young Modulus in GN/m²

G = for the Shear Modulus in GN/m², approximated to be 0.4E

ν = Poisson ratio

3.5 Quenching Treatment

Determination of the cooling behaviour of workpiece concerns transfer of heat across the surface of a body to the surrounding medium. This is mathematically expressed in terms of the heat transfer coefficient (h) (interfacial), (Totten, 2006):

$$h = q/A(T_s - T_m) \quad (3.39)$$

$$t = \rho C_p V/hA \quad (3.40)$$

Where:

h = The Heat transfer coefficient in (W/m²K)

T_s = the surface temperature of the material

T_m = temperature of the quenchant

q = Heat flux (W)

A = surface area of the workpiece in m^2

t = time required for cooling in second

ρ = Density (kg/m^3)

V = volume in m^3

The rate of cooling rate for small geometries is governed by the heat transfer coefficient and can be expressed as follow by equation (3.41) (Bylund *et al*, 2008):

$$h_c = \frac{-mC_pT}{A(T_s - T_m)} \cdot \frac{dT}{dt} \quad (3.41)$$

Where:

h_c = Heat Transfer Coefficient (Average) which is over the surface of the material

m = Mass

C_p = Specific heat capacity;

dT/dt = Temperature per unit of time

CHAPTER FOUR

4.0 RESULT AND DISCUSSIONS

4.1 Result

A simplified model to predict heat treatment planning process for annealing, soaking and quenching of aluminium alloy. The Finite Difference Method was adopted for analysing temperature of material with possible shapes (Totten, 2006). From a computational consideration, the shapes required for this analysis were plate, cylinder and bar with rectangular section, spherical and cubical materials. The analysis requires basic thermo-physical properties of the material to be heat treated as follows:

- i. Thermal conductivity
- ii. Specific heat capacity
- iii. Density
- iv. Area
- v. Volume

The Computer Aided Design (CAD) for heat treatment planning process has capability of analysing four materials with three different shapes simultaneously. In the present study the heat treatment planning process for aluminium 6061 series alloy was under taken.

4.1.2 Heat Treatment CAD Graphical User Interface

The Graphical User Interface (GUI) for the analysis involves the following stages:

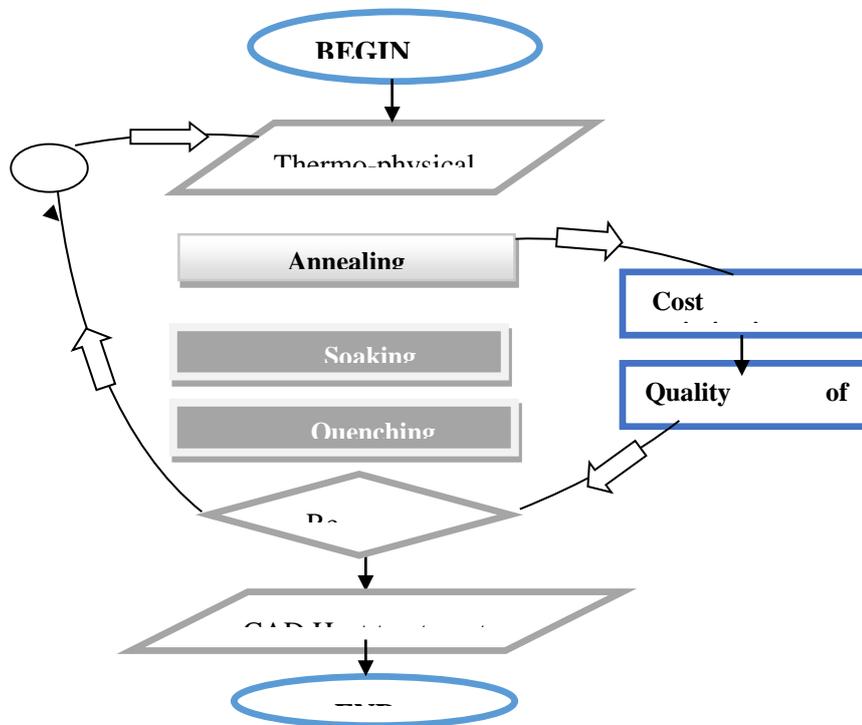


Figure 4.1: Heat treatment CAD Flow Chart

- a. material specification
- b. temperature prediction using Finite Difference Method
- c. annealing
- d. soaking
- e. quenching
- f. cost optimisation
- g. heat treatment quality prediction

The following were the details of the heat treatment CAD GUI in the study.

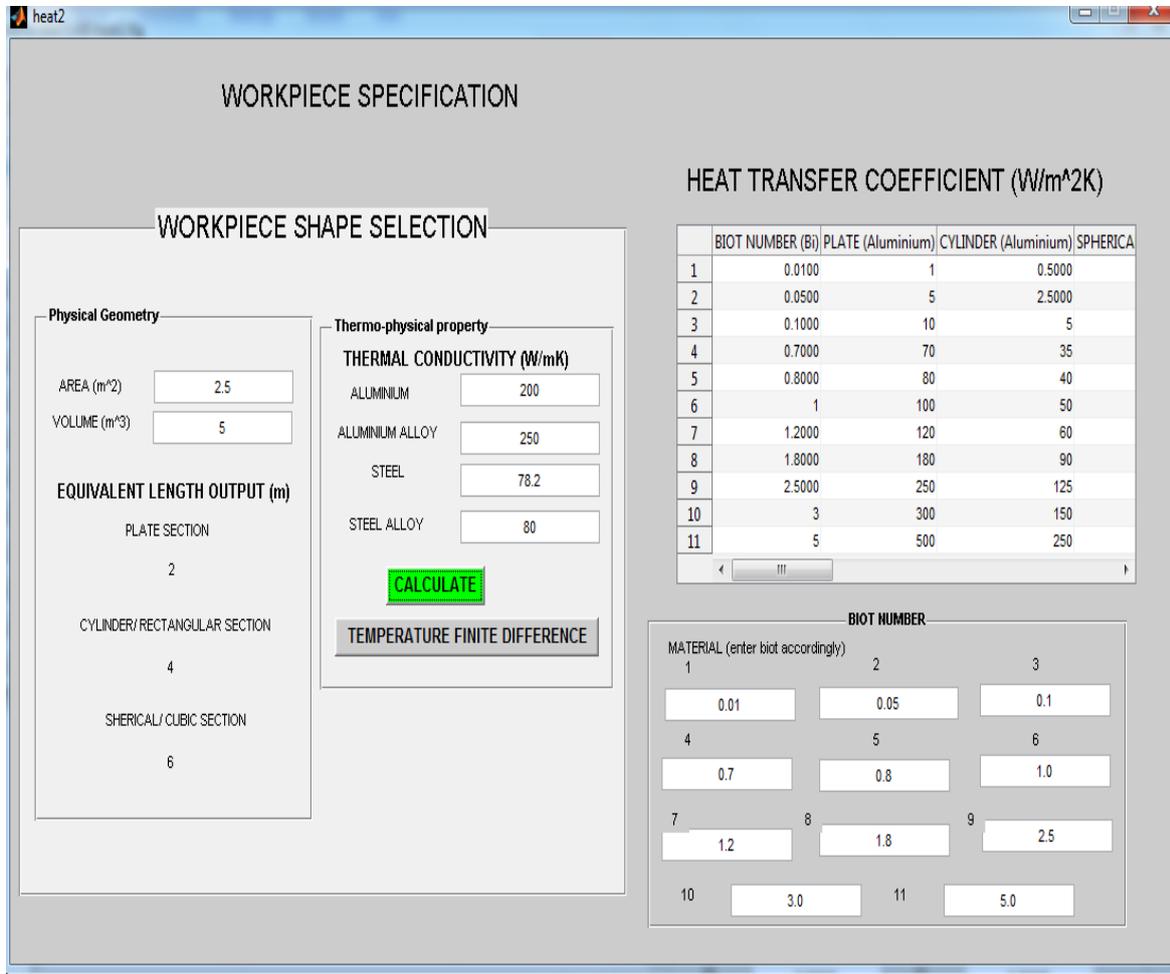


Figure 4.2: GUI for Workpiece Specification

The user workpiece selection is done by inputting physical geometry (area or volume) and thermal conductivity of the workpiece. The Biot number decides if the material is in powder (lumped) or crystal (mass) form and eleven materials are required for the analysis. The calculate button display the heat transfer coefficient of the workpiece located at the upper right corner of the GUI which displays the transfer coefficient. The equivalent lengths of treated workpiece were also known parameter. Button press of Temperature Finite Difference displays

GUI of temperature prediction by activating the button of temperature finite difference resulted in displaying the GUI of temperature prediction.

Illustrated in Figure 4.3 is the Finite difference method for heat treatment; in the GUI boundary condition are required for thermal properties of the workpiece and furnace. Incremental function, and the iteration required number are entered. The heat transfer coefficient of GUI for workpiece specification Figure 4.2 is automatically transferred to Figure 4.3. These parameters are required for temperature prediction.

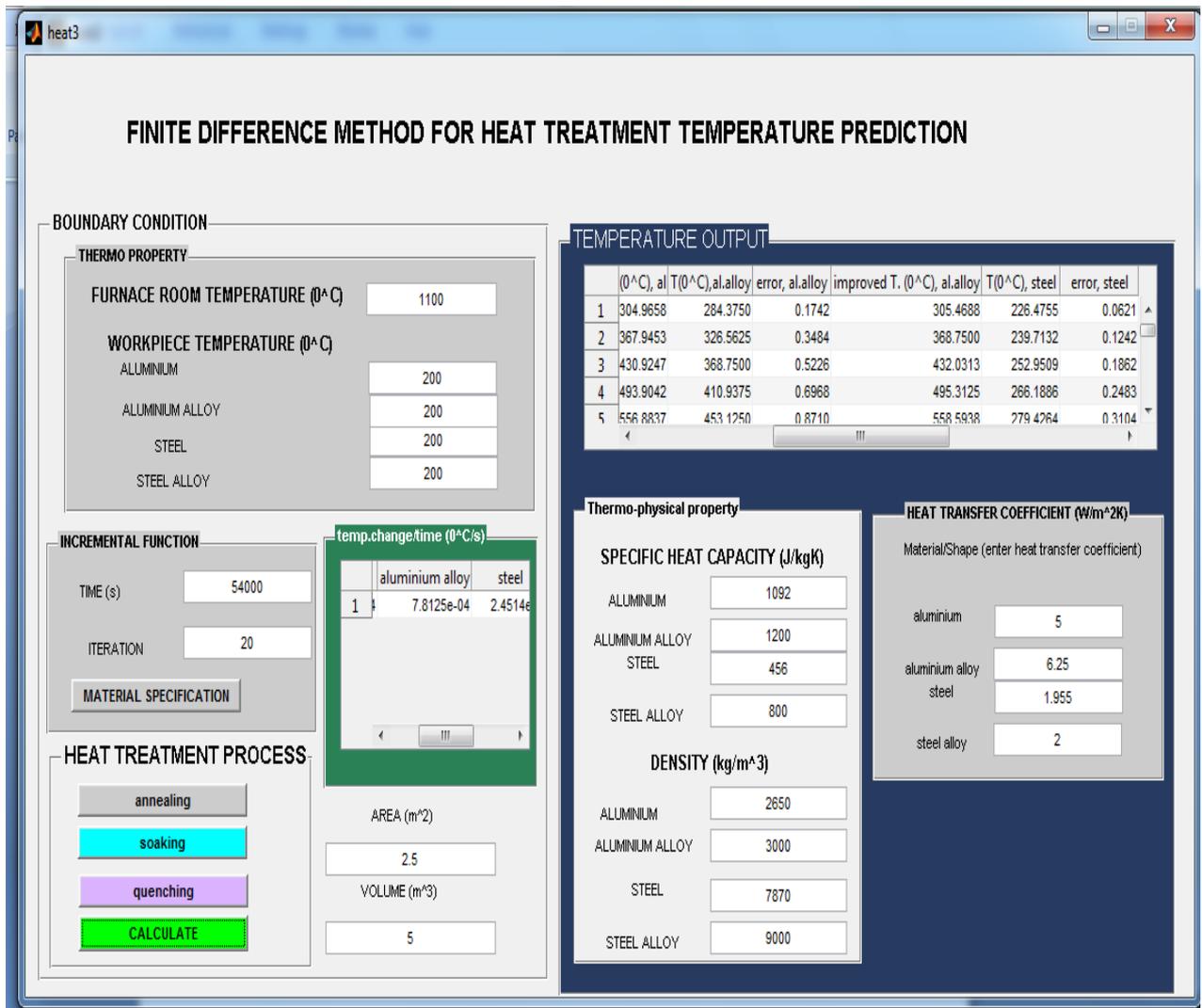


Figure 4.3: GUI for Heat treatment Temperature

4.2 Workpiece Classification

The CAD could runs for four different materials (workpiece) simultaneously. The simulation procedures were centred on the following aluminium alloys.

- i. 6061-O Annealed
- ii. 6061-T1 the workpiece Cooled from hot working and hence naturally aged
- iii. 6061-T4 the workpiece is naturally aged after solution heat treated
- iv. 6061-T6 the workpiece is finally artificial aged after solution heat treated

The required boundary condition for this study in which heat treatment simulation results were obtained is shown in table 4.1. The melting temperature of aluminium alloy was 685 °C while the heat treatment temperature was obtained at time interval of 120 seconds per iteration.

Table 4.1: Boundary Condition

Parameters	Quantity
meter	
Area of the workpiece	0.01m ² (10,000 mm ²)
Volume of the workpiece	0.00025m ³ (250,000 mm ³)
Initial Furnace temperature	50 °C
Room temperature of the alloy	32 °C
Melting Temperature of AA 6061	658 °C
Time interval	2 minute (120 seconds)
workpiece shapes	Plate, cylinder and spherical
Thermal conductivity of AA 6061 (O, T1, T4, T6)	173, 163,158 and 152 (W/mK) respectively

4.2.1 Heat Transfer Coefficient (HTC)

The results obtained in the analysis, in which equivalent treated lengths (thickness) were; plate section was 0.025m, cylinder/rectangular bar section was 0.05m; spherical and cubical was 0.075m. The heat transfer coefficients of Aluminium 6061-O, T1, T4, T6 and plate section are shown in table 4.2; 4.3; 4.4; 4.5 and 4.6 respectively.

$$Bi = \frac{ht_{eff}}{\lambda} \quad \begin{cases} < 0.1 \text{ lumped} \\ \text{otherwise massive} \end{cases} = \frac{HTC \text{ outside work piece}}{HTC \text{ inside work piece}}$$

Table 4.2: HTC of Aluminium 6061-O

Biot	Plate (W/m²K)	Cylindrical (W/m²K)	Cubic (W/m²K)
0.2	1384	692	461.3
0.3	2076	1038	692
0.4	2766	1384	922.7
0.5	3460	1730	1153
0.6	4152	2076	1384
0.7	4844	2422	1615
0.8	5536	2766	1845
0.9	6228	3114	2076
1.0	6920	3460	2307
1.1	7612	3806	2537
1.2	8304	4152	2768

The heat transfer coefficient (HTC) results for Aluminium 6061- (T1, T4) are tabulated in Tables 4.3 and 4.4 respectively for aluminium plate, cylindrical and cubic sections.

Table 4.3: HTC of Aluminium 6061-T1

Biot	Plate (W/m²K)	Cylindrical (W/m²K)	Cubic (W/m²K)
0.2	1304	652	434.7
0.3	1956	978	652
0.4	2608	1304	869.3
0.5	3260	1630	1087
0.6	3912	1956	1304
0.7	4564	2282	1521
0.8	5216	2608	1739
0.9	5868	2934	1956
1.0	6520	3260	2173
1.1	7172	3586	2391
1.2	7824	3912	2608

4.4:
of
Aluminium 6061-T4

Table
HTC

HTC result for Aluminium alloy plate, cylindrical and cubic section of 6061-T6 are tabulated in table 4.5 while table 4.6 gives summary of table 4.3; 4.4 and 4.5 for aluminium plate section only.

Table 4.5: HTC of Aluminium 6061-T6

Biot	Plate (W/m²K)	Cylindrical (W/m²K)	Cubic (W/m²K)
Biot			
0.2	1264	632	421.3
0.3	1896	948	632
0.4	2528	1264	842.7
0.5	3160	1580	1053
0.6	3792	1896	1264
0.7	4424	2212	1475
0.8	5056	2528	1685
0.9	5688	2844	1896

1.0	6320	3160	2107
1.1	6952	3476	2317
1.2	7584	3792	2528

Table 4.6: HTC of Aluminium 6061-Plate Section

Biot	Plate (W/m²K)	Cylindrical (W/m²K)	Cubic (W/m²K)	
0.2	1216	608	405.3	
0.3	1824	912	608	
0.4	2432	1216	810.7	
0.5	3040	1520	1013	
0.6	3648	1824	1216	
0.7	4256	2128	1419	
0.8	4864	2432	1621	
0.9	5472	2736	1824	
1.0	6080	3040	2027	
1.1	6688	3344	2229	
Biot	O (W/m²K)	T1 (W/m²K)	T4 (W/m²K)	T6 (W/m²K)
0.2	1384	1304	1264	1216
0.3	2076	1956	1896	1824
0.4	2766	2608	2528	2432
0.5	3460	3260	3160	3040
0.6	4152	3912	3792	3648
0.7	4844	4564	4424	4256
0.8	5536	5216	5056	4864
0.9	6228	5868	5688	5472
1.0	6920	6520	6320	6080

1.1	7612	7172	6952	6688
1.2	8304	7824	7584	7296

The summarised HTC result obtained in Table 4.6 is plotted in which HTC in W/m^2K of different plate section is plotted along y-axis while along x-axis is the equivalent Biot number of the heat treatment simulation.

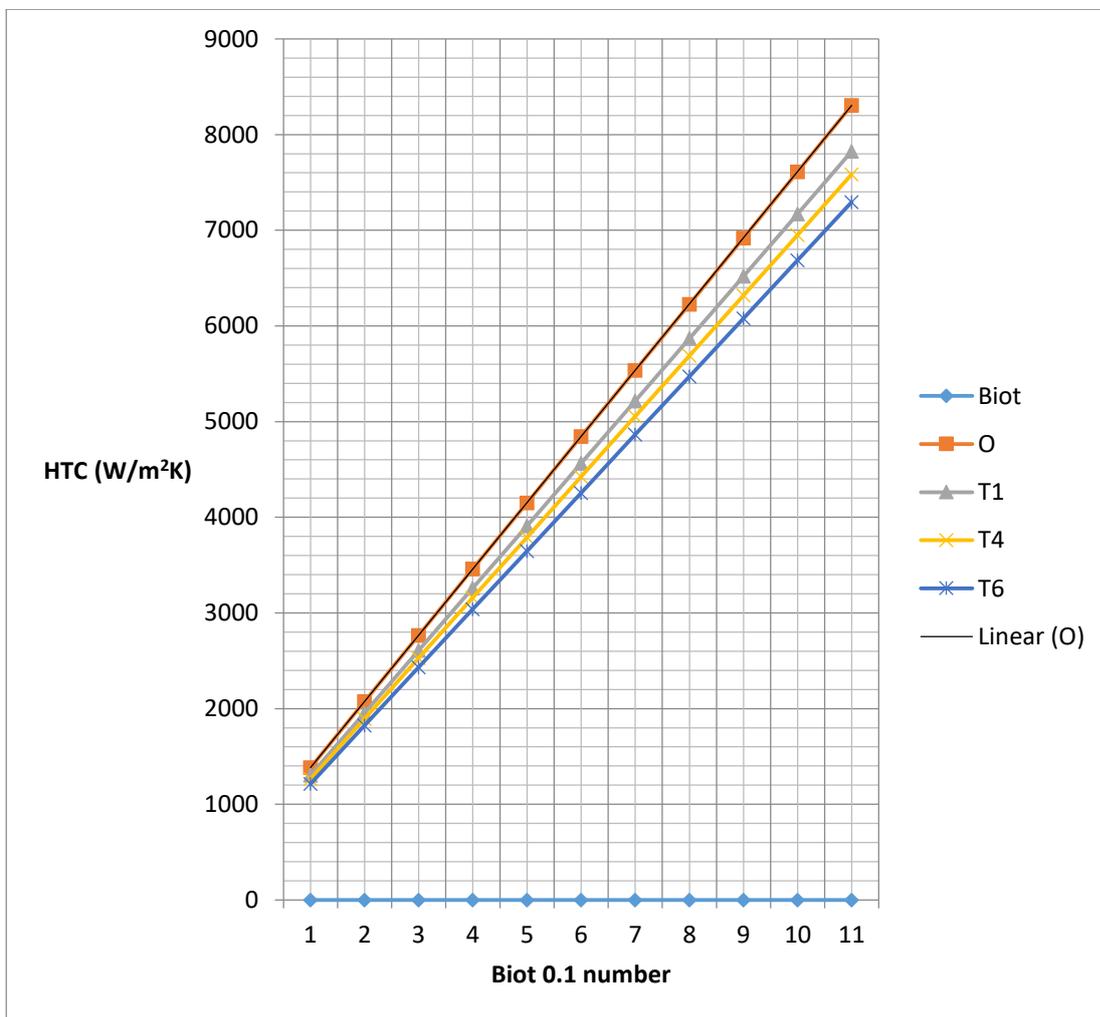


Figure 4.4: HTC of Aluminium 6061 Plate Section for various investigations on Basic tempers

4.3 Annealing Treatment

Considering melting temperature of aluminium 6061 alloy at 658 °C; one-third of the melting temperature is required for annealing treatment. The dimensionless number called Biot number was selected to quantify the rate at which heat is been transferred in the alloy. Thus, Biot number of 0.2 was selected for this analysis. Therefore, heat transfer coefficient (HTC) for Aluminium (6061-O, T1, T4, T6) with 1384, 1304, 1264 and 1216 W/m²K were selected for annealing treatment and they were shown in table 4.7; 4.8; 4.9 and 4.10 respectively.

Table 4.7: Aluminium 6061-O Plate of HTC 1384 W/m²K

Time (s)	Heating Temp. (°C)	Improved Temp (°C)
60	81.4	93.8
180	130.9	167.9
300	180.3	242.1
420	229.7	316.2
540	279.1	390.4
660	328.6	464.5
780	378	538.6
900	427.4	612.8
1020	476.9	686.9

1140	526.3	761.1
1260	575.7	835.2
1380	625.1	909.4
1500	674.6	983.5
1620	724	1057.6
1740	773	1131.8

HTC (1304, 1264 W/m²K) for Aluminium 6061- (T1, T6) plate section are respectively selected for annealing treatment. The result are Tabulated in table 4.8 and 4.9 accordingly.

Table 4.8: Aluminium 6061-T1 Plate of HTC 1304 W/m²K

Time (s)	Heating Temp. (°C)	Improved Temp (°C)
60	78.6	90.2
180	125.1	160.1
300	171.7	229.9
420	218	299.8
540	264.9	369.6
660	311.4	439.5
780	358	509
900	404.5	579.2
1020	451.1	649.1

1140	497.7	718.9
1260	544.3	788.8
1380	590.9	858.6
1500	637.4	928.5
1620	684	998.4
1740	730.6	1068.2

Table 4.9: Aluminium 6061-T4 Plate of HTC 1264 W/m²K

Time (s)	Heating Temp. (°C)	Improved Temp (°C)
60	77.1	88.4
180	122.3	156.1
300	167.4	223.9
420	212.6	291.6
540	257.7	359.3
660	302.9	427
780	348	494.7
900	393.1	562.4
1020	438.3	630.1
1140	483.4	697.9
1260	528.6	765.6
1380	573.7	833.3
1500	618.9	901
1620	664	968.7
1740	709.1	1036.4

HTC of 1216 W/m²K for Aluminium 6061- T6 plate section are selected for annealing treatment as in Table 4.10. Figure 4.5 is the graph of Aluminium 6061 plate heating temperature per unit of time. In the x-axis each unit is 120 seconds.

Table 4.10: Aluminium 6061-T6 Plate of HTC 1216 W/m²K

Time (s)	Heating Temp. (°C)	Improved Temp (°C)
60	75.4	86.3
180	118.9	151.4
300	162.3	216.6
420	205.7	281.7
540	249.1	346.9
660	292.6	412
780	336	477
900	379.4	542.3
1020	422.9	607.4
1140	466.2	672.6
1260	509.7	737.7
1380	533.1	802.9
1500	596.6	868
1620	640	933.1
1740	683.4	998.3

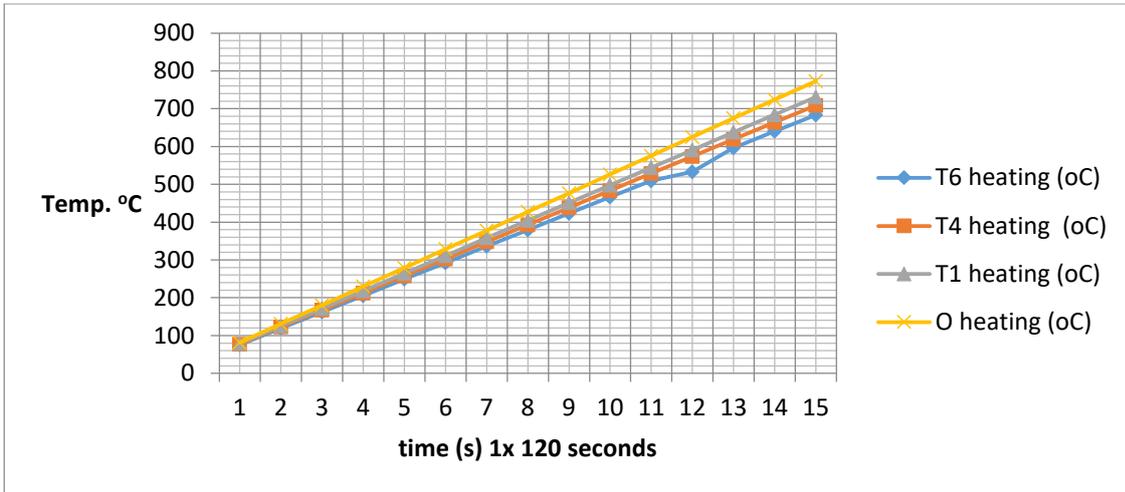


Figure 4.5: Aluminium 6061 Plate heating temperature per unit time (°C)

Figure 4.6 is the graph of Aluminium 6061-O plate section for which heating temperature and improved or maximum expected heating temperature per unit of time is plotted. In the x-axis each unit is 120 seconds.

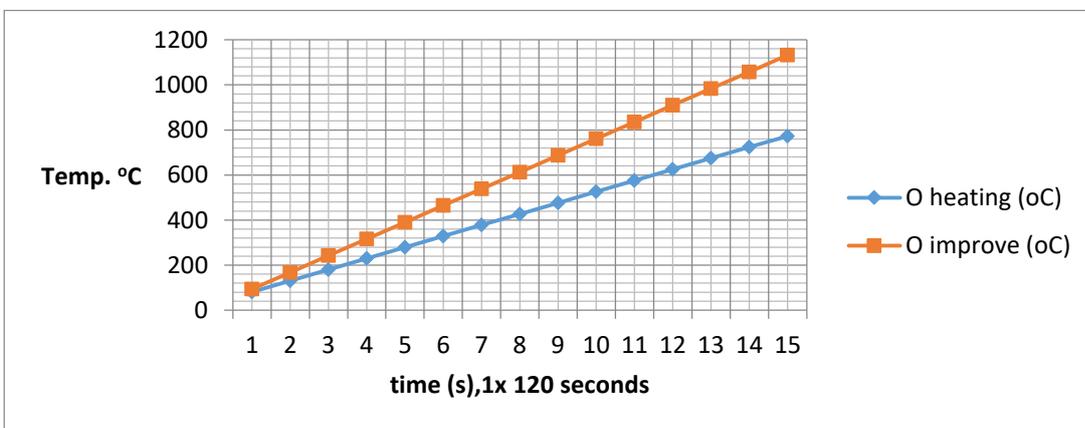


Figure 4.6: Aluminium 6061-O Plate heating temperature per unit time (°C)

4.3.1 Elastic Recovery of Aluminium 6061

Elastic recovery is non-permanent deformation that is recovered or regained upon the release of a mechanical stress as in Table 4.11 for plate of volume, 0.00025m^3 . $U_r = \frac{\sigma_y^2}{2E}$, $E= 70\text{GPa}$.

Table 4.11: Elastic Recovery of Aluminium 6061- Plate

Material	Yield (MPa),	Strength σ_y	Resilience (J/m ³),	U_r	Recovered Energy (μJ),	E
O	125		0.022		5.5	
T1	160		0.052		13	
T4	207		0.086		21.5	
T6	310		0.54		135	

Since 0.00025 m^3 of plate was employed in the analysis, therefore quantity of energy required for regaining the plate's elasticity as were given in Table 4.11.

4.3.2 Sample of Mechanical Properties of the alloy Plate (6061-O)

Table 4.12 was the recrystallisation and mechanical property of the aluminium plate with Biot number 0.20 and HTC of $1384\text{ W/m}^2\text{K}$ while Table 4.13 is the solid solution temperature of the treatment. The room temperature of the plate after cold work was $32\text{ (}^\circ\text{C)}$. The graph of solid-solution temperature of plate (aluminium 6061-O) per unit of time is in Figure 4.7 in which annealing temperature was plotted for aluminium 6061-O alloying plate.

Table 4.12: Mechanical Property of Aluminium alloy Plate 6061-O

Time in (s)	Heating Temp. (°C)	ΔT, T (°C)	Elongation $\epsilon = \alpha \Delta T$	Stress $\sigma = E\epsilon$, (MPa)	Ductility $\sigma = \epsilon * 100\%$,
60	81.4	49.4	0.001	70	0.1
180	130.9	98.9	0.002	140	0.2
300	180.3	148.3	0.004	280	0.4
420	229.7	197.7	0.005	350	0.5
540	279.1	247.1	0.006	420	0.6
660	328.6	296.6	0.007	490	0.7
780	378	328.6	0.008	560	0.8
900	427.4	395.4	0.009	630	0.9
1020	476.9	444.9	0.011	770	1.1
1140	526.3	494.3	0.012	840	1.2
1260	575.7	543.7	0.013	910	1.3
1380	625.1	593.1	0.014	980	1.4
1500	674.6	642.6	0.015	1050	1.5
1620	724	692	0.016	1120	1.6
1740	773	741	0.017	1190	1.7

Table 4.13: Solid Solution Temperature of Aluminium alloy Plate 6061-O

Time (s)	Heating Temp. (°C)	ΔT, T (°C)	Strain $\epsilon = \alpha \Delta T$	Stress $\sigma = E\epsilon$, (MPa)	Ductility $\sigma = \epsilon * 100\%$,
-----------------	---------------------------	--------------------------------------	---	--	--

60	81.4	49.4	0.001	70	0.1
65	83.6	51.6	0.001	70	0.1
180	130.9	98.9	0.002	140	0.2
288	175.5	143.5	0.003	210	0.3
300	180.3	148.3	0.004	280	0.4
336	195	163	0.004	280	0.4
420	229.7	197.7	0.005	350	0.5
540	279.1	247.1	0.006	420	0.6
660	328.6	296.6	0.007	490	0.7
780	378	328.6	0.008	560	0.8
857	409.5	377.5	0.009	630	0.9
900	427.4	395.4	0.009	630	0.9
1020	476.9	444.9	0.011	770	1.1
1140	526.3	494.3	0.012	840	1.2
1260	575.7	543.7	0.013	910	1.3
1283	585	553	0.013	910	1.3
1380	625.1	593.1	0.014	980	1.4

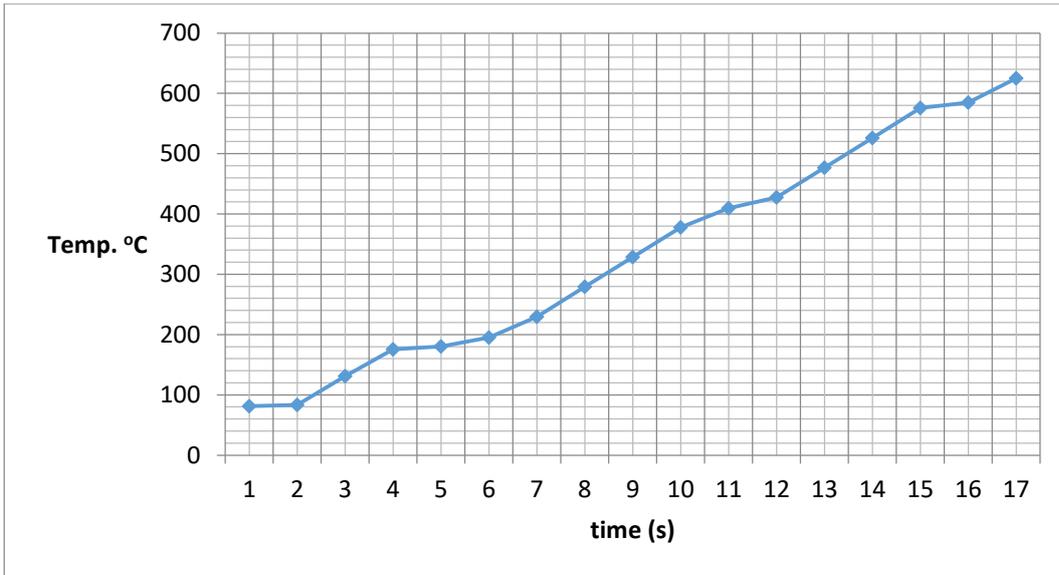


Figure 4.7: Annealing Temperature curve

Figure 4.8 is Stress (MPa)-Strain of 0.001 per unit graph which are estimated during annealing treatment and plotted for aluminium 6061-O alloying plate.

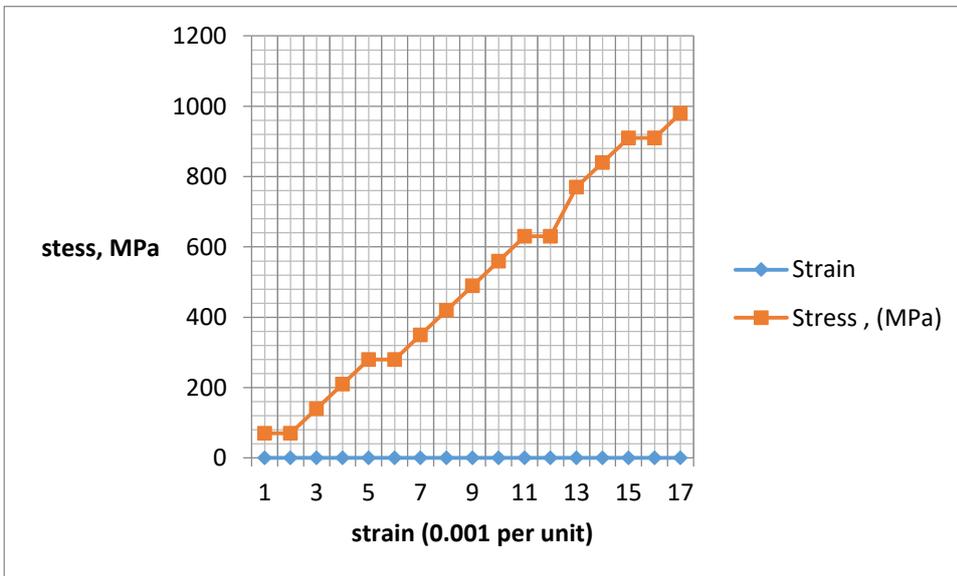


Figure 4.8: Stress - Strain relationship

The hardness of the analysis was estimated in terms of tensile strength as, $\sigma = 3.45 \times HB$ (Callister.Jr. 2001) and shown in Table 4.14.

Table 4.14: Hardness of Aluminium Plate 6061-O base on Solid Solution

Temp. (°C)	Ductility $\sigma = \epsilon * 100\%$,	Strain $\epsilon = \alpha\Delta T$	Stress $\sigma = E\epsilon$, (MPa)	Brinell Hardness, <i>MPa</i>
73.5	0.08	0.0008	55	15.94
81.4	0.10	0.0010	70	20.29
83.6	0.10	0.0010	70	20.29
103.7	0.14	0.0014	100	29.00
120.7	0.18	0.0018	125	36.23
130.9	0.20	0.002	140	40.58
175.5	0.30	0.003	210	60.87
180.3	0.40	0.004	280	81.15
195	0.40	0.004	280	81.15

4.4 Soaking Temperature

The AAW plate of Biot number 0.20 with HTC of 1384 W/m²K was soaked for 10 minute (600seconds) which means annealing treatment was done ‘without change in temperature’ at this period. Situation of temperature uniformity was experienced, therefore according to equation (3.38), we had elasticity of the plate to be 74.5GPa. The soaking was done at recrystallisation temperature of 409.5 °C after 857 seconds of time as shown in Table 4.15.

Table 4.15: Yield Strength of Aluminium Plate 6061-O base on Soaking

Heating Temp. (°C)	Ductility	Strength
	$\sigma = \epsilon * 100\%$,	$\sigma = E\epsilon, \text{ (MPa)}$
73.5	0.08	59.6
83.6	0.1	74.5
103.7	0.14	104.3
120.7	0.18	134.1
131	0.2	149
175.5	0.3	223.5
195	0.4	298
409.5	0.90	670.5

Yield strength of 149 MPa

Ultimate tensile strength of 298 MPa

Fracture resistance of 670.5 MPa

4.5 Quenching

HTC of quenching media is shown in Table 4.16 (Fontecchio 2002) while Table 4.17 quenching of the plate in water. Thus, quenching factor, QF is the ratio of HTC of the material to HTC of quenchant (Fontecchio 2002). The plate HTC was 1384 W/m²K of Biot 0.2.

Table 4.16: Quenchant

Quenchant	Quenchant HTC	Quenching Factor QF,
Brine or Causatic Soda	3600	0.38
Water	3200	0.43
Oil	1200	1.15
Bath Salt	400	3.46
Air	100	13.84

**Table 4.17:
Quenching of
Plate in Water**

the

Temp. °C	Time (s)
409.5	0
176	488
75.7	699
32.6	789
28	799

Quenching temperature per unit of time is plotted in Figure 4.9 for aluminium 6061-O alloying plate.

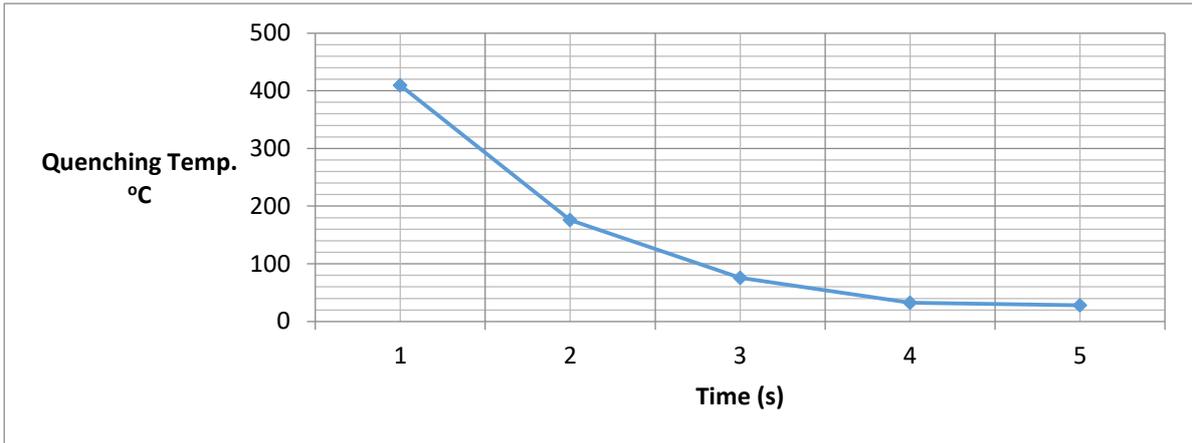


Figure 4.9: Quenching per unit time

4.6 Complete Heat Treatment of the Plate

The complete process of plate heat treatment of Biot number 0.20 is indicated in table 4.18 and figure 4.10.

Table 4.18: Total Heat Treatment in the Plate

Time (s)	Heating Temp. T, (°C)
60	81.4
65	83.6
180	130.9
288	175.5
300	180.3
336	195
420	229.7
540	279.1
660	328.6
780	378
857	409.5
1457	409.5
1945	176
2156	75.7
2246	32.6
2256	28

The total temperature history for annealing, soaking and quenching heat treatment process for aluminium 6061-O alloying plate is plotted in Figure 4.10.

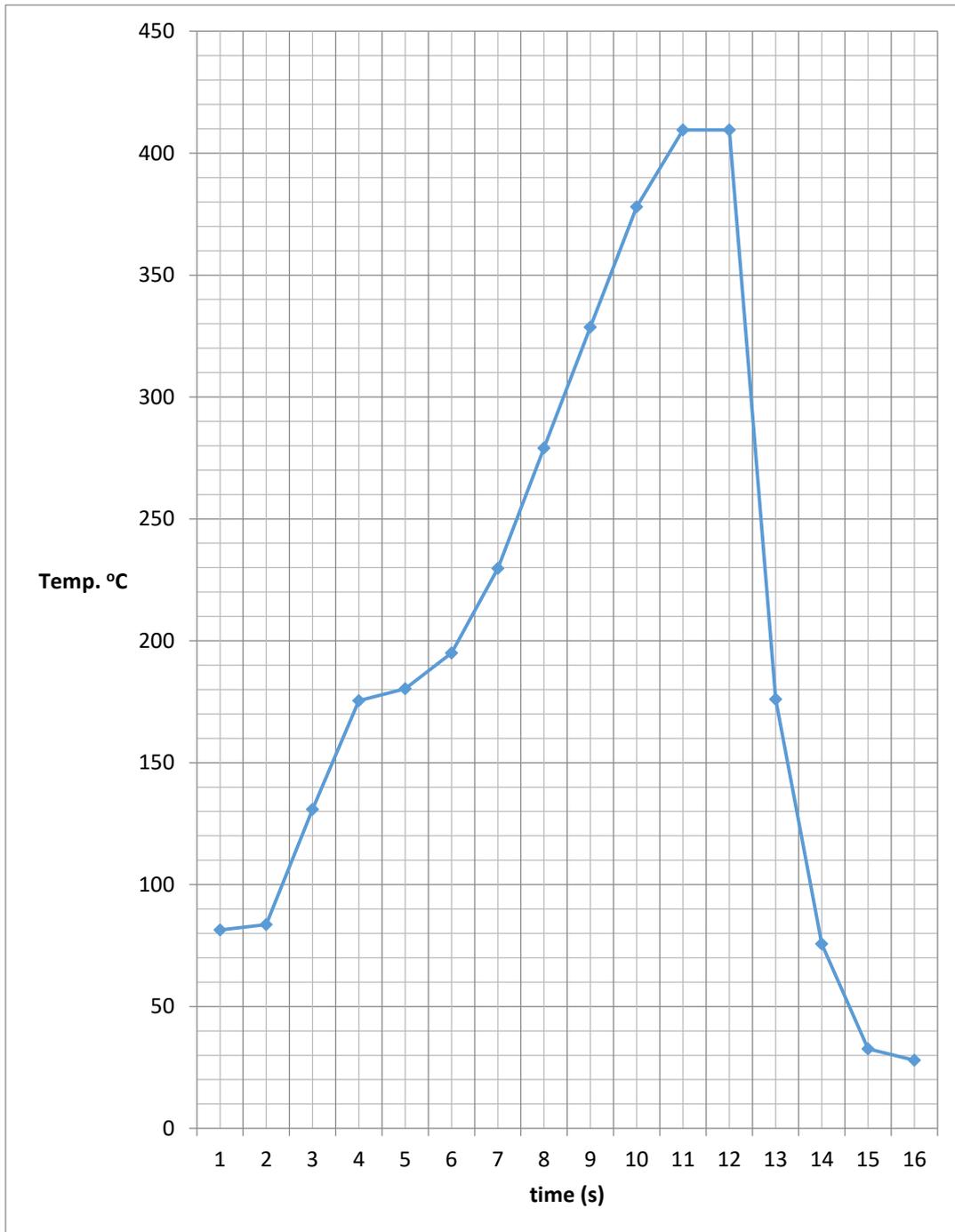


Figure 4.10: Complete Temperature history of Heat Treatment Process

4.7 Discussions

Aluminium alloy was employed for the analysis which was classified by Biot number. However, the initial temperature for the specimen in the experiment was set at 32 °C as input for the simulation. Geometry of the specimen was 0.01m² and 0.00025m³ for area and volume respectively. Furnace initial temperature was set at 50 °C, total heat treatment time was 2256 seconds. The treated AAW 6061 (O, T1, T4 and T6) specimens were plate, cylinder and spherical workpiece.

The rate of heat transfer was obtained in the specimen with equivalent treated thickness of 25mm in plate, 50mm in cylinder/rectangular bar and 75mm in spherical object. The rate of heat transfer across aluminium specimen 6061 (O, T1, T4 and T6) was shown in Table 4.2. Heat transfer coefficient (HTC) rate across the workpiece were: 1384, 692, and 461.3 W/m²K, in plate, cylinder and spherical specimen respectively for Biot number of 0.2. Selecting of Biot number of 0.2 shows that AAW-6061-O has highest of HTC with 1384 W/m²K and lowest in AAW-6061-O with 1216 W/m²K of HTC in same plate section. HTC of plate were plotted in Figure 4.4 and 4.5. Figure 4.6 shows that possible temperature that could be achieved after 600 seconds were 280 and 400 °C (minimum and maximum respectively).

The term annealing heat treatment could be explained in which a material is subjected to an elevated temperature for a period of time and then slowly cooled in a desire medium. Generally, annealing is been carried out to:

- i. improve ductility and toughness
- ii. relieve stresses of cold working
- iii. induce softness

iv. To produce a specific desire microstructure.

The annealing processes include heating to the appropriate temperature, then soaked at that temperature, and allow cooling, which is usually to room temperature. Plate specimen was selected for annealing processes. After 900 seconds of solution treatment, we had temperature of 427.4 °C as minimum possible and 612.8 °C maximum in Table 4.7 for AAW-6061(O). Treatment must below pure aluminium melting temperature of 600 °C, therefore recrystallisation temperature of 409.5 °C falls within this region for plate AAW-6061(O). On 900 seconds, plate AAW-6061(T6) had minimum temperature of 379.4 °C and maximum temperature of 542.3 °C as in Table 4.10.

The resilience was 0.022 J/m³ for plate AAW-6061(O) as shown in table 4.11; the lowest. In table 4.12, solid solution temperature to be achieved was 585 °C and has to be prevented for complete solutionizing. The percent ductility was at 1.3% at 585 °C, the same ductility was achieved at 575.7 °C, and therefore solutionizing has been achieved at 575.7 °C at 1260 seconds in comparison to 1283 seconds for 585 °C. In Figure 4.8 ultimate strength of the AAW-6061(O) was 125MPa at strain of 0.0025 before soaking. Elasticity of the plate was improved due to soaking of about 600 seconds. The Young modulus was 70GPa before soaking and on soaking 74.5 GPa was achieved. The soaking was done at recrystallisation temperature of 409.5 °C (0.7 of solid solution temperature of 585 °C) after 857 seconds.

However, yield strength of 149 MPa at temperature of 131°C after soaking and ultimate strength of 298 MPa at 195°C.

Quenching in brine or caustic soda is better while in air was good according to quenching factor in Table 4.16. For AAW plate quenching in water was considered because most AAW are quenched in water. The quenching took place from temperature of 409.5 °C to temperature of 28 °C after 799 seconds. The heat treatment was completed after 2256 seconds for the plate

AAW-6061(O). Annealing at 409.5 °C resulted to ultimate tensile strength value (298 MPa) and fracture resistance of 670.5MPa as in Table 4.15.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Annealing heat treatment comprises heating of a metal workpiece that will reach a predetermined temperature and allow cooling at a rate such that it will result in and give a refined microstructure. This method is usually used to induce softness in a workpiece for cold working, or could be used to enhance machinability, or improve the properties of the workpiece such as electrical conductivity. However, in most pure metals and its alloys that cannot undergo heat treatment. Annealing processes are sometimes adopted to address the problem of hardness as a result of cold working. The aluminium alloy workpiece is heated to an appropriate temperature where recrystallisation could occur, hence repairing the noticeable associated problems due to plastic deformation. Also, the rate of cooling of these metals is often having a small effect. Therefore, most non-ferrous alloys such as aluminum alloys 6061 that could be heat-treatable are annealed which usually assist in removing the hardness of cold working. It will then, slowly cooled to permit complete full precipitation and thus, form a refined microstructure.

However, heat treatment in plate section of aluminium (AAW-6061-O) was faster in comparing to rectangular and cylindrical surfaces. HTC was $1384 \text{ W/m}^2\text{K}$ in plate and $692 \text{ W/m}^2\text{K}$ in cylindrical specimen of Biot number 0.2. The higher Biot number higher rate of heat transfer coefficient in AAW specimen. At annealing temperature of $409.5 \text{ }^\circ\text{C}$ we had fracture resistance of 670.5 MPa and ultimate tensile strength value 298 MPa was achieved with 4% of ductility. The heat treatment processing was completed after 2256 seconds and AAW-6061-O is more easily heat treatable to AAW-6061- (T1, T4, T6) under the same condition.

5.2 Recommendations for Further Study

Further studies are recommended in the following areas:

- i. Effect of heat treatment on corrosion resistance of a workpiece of 6061 aluminium alloy
- ii. Effect of the heat treatment in microstructures of spring aluminium alloy
- iii. The optimisation cost of aluminum alloy heat treatment quality
- iv. Experimental analysis of heat treatment of aluminium alloy welding pool
- v. Effect of heat treatment on machining of aluminum alloy workpiece

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MATLAB SOURCE CODE

```
% HEAT2 M-file for heat2.fig
% HEAT2, by itself, creates a new HEAT2 or raises the existing
% singleton*.
%
% H = HEAT2 returns the handle to a new HEAT2 or the handle to
% the existing singleton*.
%
% HEAT2('CALLBACK',hObject,eventData,handles,...) calls the local
% function named CALLBACK in HEAT2.M with the given input arguments.
%
% HEAT2('Property','Value',...) creates a new HEAT2 or raises the
% existing singleton*. Starting from the left, property value pairs are
% applied to the GUI before heat2_OpeningFcn gets called. An
% unrecognized property name or invalid value makes property application
```

```

%      stop.  All inputs are passed to heat2_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help heat2

% Last Modified by GUIDE v2.5 04-Feb-2012 15:46:14

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',  gui_Singleton, ...
                  'gui_OpeningFcn', @heat2_OpeningFcn, ...
                  'gui_OutputFcn',  @heat2_OutputFcn, ...
                  'gui_LayoutFcn',  [] , ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before heat2 is made visible.
function heat2_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to heat2 (see VARARGIN)

% Choose default command line output for heat2
handles.output = hObject;
num = 0;
handles.edit1 = num;
handles.edit2 = num;
handles.edit6 = num;
handles.edit7= num;
handles.edit8= num;
handles.edit9 = num;
handles.edit10 = num;
handles.edit11 = num;
handles.edit12= num;
handles.edit13 = num;
handles.edit14 = num;
handles.edit15= num;
handles.edit16= num;
handles.edit17 = num;
handles.edit18 = num;
handles.edit19= num;
handles.edit20 = num;
handles.edit21 = num;
handles.edit22= num;
handles.edit23 = num;
handles.edit24 = num;
handles.edit25= num;
handles.edit26 = num;
handles.edit27 = num;
handles.edit28= num;

% Declare cache for selection, which starts out empty
handles.currSelection = [];
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes heat2 wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.

```

```

function varargout = heat2_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

function edit1_Callback(hObject, eventdata, handles)
% hObject handle to edit1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
% str2double(get(hObject,'String')) returns contents of edit1 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit1 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit2_Callback(hObject, eventdata, handles)
% hObject handle to edit2 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
% str2double(get(hObject,'String')) returns contents of edit2 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit2 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit2 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit6_Callback(hObject, eventdata, handles)
% hObject handle to edit6 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

```

```

% Hints: get(hObject,'String') returns contents of edit6 as text
%         str2double(get(hObject,'String')) returns contents of edit6 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit6 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit6_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit6 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%         str2double(get(hObject,'String')) returns contents of edit7 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit7 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit8 as text
%         str2double(get(hObject,'String')) returns contents of edit8 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit8 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)

```

```

% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit9_Callback(hObject, eventdata, handles)
% hObject handle to edit9 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
% str2double(get(hObject,'String')) returns contents of edit9 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit9 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit9_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit9 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit10_Callback(hObject, eventdata, handles)
% hObject handle to edit10 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10 as text
% str2double(get(hObject,'String')) returns contents of edit10 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit10 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit10_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit10 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit11_Callback(hObject, eventdata, handles)
% hObject handle to edit11 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

```

```

% Hints: get(hObject,'String') returns contents of edit11 as text
%         str2double(get(hObject,'String')) returns contents of edit11 as a double

num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit11 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit12_Callback(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit12 as text
%         str2double(get(hObject,'String')) returns contents of edit12 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit12 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit12_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit13_Callback(hObject, eventdata, handles)
% hObject    handle to edit13 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit13 as text
%         str2double(get(hObject,'String')) returns contents of edit13 as a double

num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit13 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit13_CreateFcn(hObject, eventdata, handles)

```

```

% hObject    handle to edit13 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit14_Callback(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit14 as text
%        str2double(get(hObject,'String')) returns contents of edit14 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit14 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit14_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit15_Callback(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit15 as text
%        str2double(get(hObject,'String')) returns contents of edit15 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit15 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit15_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit16_Callback(hObject, eventdata, handles)
% hObject    handle to edit16 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB

```

```

% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit16 as text
%        str2double(get(hObject,'String')) returns contents of edit16 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit16 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit16_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit16 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit17_Callback(hObject, eventdata, handles)
% hObject    handle to edit17 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit17 as text
%        str2double(get(hObject,'String')) returns contents of edit17 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit17 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit17_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit17 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit18_Callback(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit18 as text
%        str2double(get(hObject,'String')) returns contents of edit18 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit18 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.

```

```

function edit18_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit19_Callback(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit18 as text
%         str2double(get(hObject,'String')) returns contents of edit18 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit19 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit19_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit18 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit20_Callback(hObject, eventdata, handles)
% hObject    handle to edit20 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit20 as text
%         str2double(get(hObject,'String')) returns contents of edit20 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit20 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit20_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit20 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit21_Callback(hObject, eventdata, handles)
% hObject    handle to edit21 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB

```

```

% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit21 as text
%        str2double(get(hObject,'String')) returns contents of edit21 as a double

num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit21 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit21_CreateFcn(hObject, eventdata, handles)
% hObject      handle to edit21 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%           See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit22_Callback(hObject, eventdata, handles)
% hObject      handle to edit22 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit22 as text
%        str2double(get(hObject,'String')) returns contents of edit22 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit22 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit22_CreateFcn(hObject, eventdata, handles)
% hObject      handle to edit22 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%           See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit23_Callback(hObject, eventdata, handles)
% hObject      handle to edit23 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit23 as text
%        str2double(get(hObject,'String')) returns contents of edit23 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit23 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit23_CreateFcn(hObject, eventdata, handles)
% hObject      handle to edit23 (see GCBO)

```

```

% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit24_Callback(hObject, eventdata, handles)
% hObject handle to edit24 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit24 as text
% str2double(get(hObject,'String')) returns contents of edit24 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit24 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit24_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit24 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit25_Callback(hObject, eventdata, handles)
% hObject handle to edit25 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit25 as text
% str2double(get(hObject,'String')) returns contents of edit25 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit25 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit25_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit25 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit26_Callback(hObject, eventdata, handles)
% hObject handle to edit26 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit26 as text

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%         str2double(get(hObject,'String')) returns contents of edit26 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit26 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit26_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit26 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit27_Callback(hObject, eventdata, handles)
% hObject    handle to edit27 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit27 as text
%         str2double(get(hObject,'String')) returns contents of edit27 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit27 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit27_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit27 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%         See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit28_Callback(hObject, eventdata, handles)
% hObject    handle to edit28 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit28 as text
%         str2double(get(hObject,'String')) returns contents of edit28 as a double
num = str2double(get(hObject,'String'));
if isnan(num)
    num = 0;
    set(hObject,'String',num);
    errordlg('Input must be a number', 'Error')
end
handles.edit28 = num;
guidata(hObject,handles)

% --- Executes during object creation, after setting all properties.
function edit28_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit28 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

```

```

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% determination of heat transfer coefficient
% on the first column of H (BIOT NUMBER)
H(1,1)=handles.edit18;
H(2,1)=handles.edit19;
H(3,1)=handles.edit20;
H(4,1)=handles.edit21;
H(5,1)=handles.edit22;
H(6,1)=handles.edit23;
H(7,1)=handles.edit24;
H(8,1)=handles.edit25;
H(9,1)=handles.edit26;
H(10,1)=handles.edit27;
H(11,1)=handles.edit28;
set(handles.H,'Data', H);
% aluminium and alloy
% plate lenght
text1h=handles.edit2/handles.edit1;
set(handles.text1h,'String', text1h);
% cylinder lenght
text2h=2*handles.edit2/handles.edit1;
set(handles.text2h,'String', text2h);
% spherical lenght
text3h=3*handles.edit2/handles.edit1;
set(handles.text3h,'String', text3h);
% plate heat transfer
H(1,2)=handles.edit6*handles.edit18/(text1h);
H(2,2)=handles.edit6*handles.edit19/(text1h);
H(3,2)=handles.edit6*handles.edit20/(text1h);
H(4,2)=handles.edit6*handles.edit21/(text1h);
H(5,2)=handles.edit6*handles.edit22/(text1h);
H(6,2)=handles.edit6*handles.edit23/(text1h);
H(7,2)=handles.edit6*handles.edit24/(text1h);
H(8,2)=handles.edit6*handles.edit25/(text1h);
H(9,2)=handles.edit6*handles.edit26/(text1h);
H(10,2)=handles.edit6*handles.edit27/(text1h);
H(11,2)=handles.edit6*handles.edit28/(text1h);
H(1,5)=handles.edit7*handles.edit18/(text1h);
H(2,5)=handles.edit7*handles.edit19/(text1h);
H(3,5)=handles.edit7*handles.edit20/(text1h);
H(4,5)=handles.edit7*handles.edit21/(text1h);
H(5,5)=handles.edit7*handles.edit22/(text1h);
H(6,5)=handles.edit7*handles.edit23/(text1h);
H(7,5)=handles.edit7*handles.edit24/(text1h);
H(8,5)=handles.edit7*handles.edit25/(text1h);
H(9,5)=handles.edit7*handles.edit26/(text1h);
H(10,5)=handles.edit7*handles.edit27/(text1h);
H(11,5)=handles.edit7*handles.edit28/(text1h);
set(handles.H,'Data', H);
% cylinder heat transfer
H(1,3)=handles.edit6*handles.edit18/(text2h);
H(2,3)=handles.edit6*handles.edit19/(text2h);
H(3,3)=handles.edit6*handles.edit20/(text2h);
H(4,3)=handles.edit6*handles.edit21/(text2h);
H(5,3)=handles.edit6*handles.edit22/(text2h);
H(6,3)=handles.edit6*handles.edit23/(text2h);
H(7,3)=handles.edit6*handles.edit24/(text2h);
H(8,3)=handles.edit6*handles.edit25/(text2h);
H(9,3)=handles.edit6*handles.edit26/(text2h);
H(10,3)=handles.edit6*handles.edit27/(text2h);
H(11,3)=handles.edit6*handles.edit28/(text2h);
H(1,6)=handles.edit7*handles.edit18/(text2h);
H(2,6)=handles.edit7*handles.edit19/(text2h);
H(3,6)=handles.edit7*handles.edit20/(text2h);
H(4,6)=handles.edit7*handles.edit21/(text2h);

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H(5,6)=handles.edit7*handles.edit22/(text2h);
H(6,6)=handles.edit7*handles.edit23/(text2h);
H(7,6)=handles.edit7*handles.edit24/(text2h);
H(8,6)=handles.edit7*handles.edit25/(text2h);
H(9,6)=handles.edit7*handles.edit26/(text2h);
H(10,6)=handles.edit7*handles.edit27/(text2h);
H(11,6)=handles.edit7*handles.edit28/(text2h);
set(handles.H,'Data', H);
% spherical heat transfer
H(1,4)=handles.edit6*handles.edit18/(text3h);
H(2,4)=handles.edit6*handles.edit19/(text3h);
H(3,4)=handles.edit6*handles.edit20/(text3h);
H(4,4)=handles.edit6*handles.edit21/(text3h);
H(5,4)=handles.edit6*handles.edit22/(text3h);
H(6,4)=handles.edit6*handles.edit23/(text3h);
H(7,4)=handles.edit6*handles.edit24/(text3h);
H(8,4)=handles.edit6*handles.edit25/(text3h);
H(9,4)=handles.edit6*handles.edit26/(text3h);
H(10,4)=handles.edit6*handles.edit27/(text3h);
H(11,4)=handles.edit6*handles.edit28/(text3h);
H(1,7)=handles.edit7*handles.edit18/(text3h);
H(2,7)=handles.edit7*handles.edit19/(text3h);
H(3,7)=handles.edit7*handles.edit20/(text3h);
H(4,7)=handles.edit7*handles.edit21/(text3h);
H(5,7)=handles.edit7*handles.edit22/(text3h);
H(6,7)=handles.edit7*handles.edit23/(text3h);
H(7,7)=handles.edit7*handles.edit24/(text3h);
H(8,7)=handles.edit7*handles.edit25/(text3h);
H(9,7)=handles.edit7*handles.edit26/(text3h);
H(10,7)=handles.edit7*handles.edit27/(text3h);
H(11,7)=handles.edit7*handles.edit28/(text3h);
set(handles.H,'Data', H);

% aluminium alloy and alloy
% plate heat transfer
H(1,8)=handles.edit8*handles.edit18/(text1h);
H(2,8)=handles.edit8*handles.edit19/(text1h);
H(3,8)=handles.edit8*handles.edit20/(text1h);
H(4,8)=handles.edit8*handles.edit21/(text1h);
H(5,8)=handles.edit8*handles.edit22/(text1h);
H(6,8)=handles.edit8*handles.edit23/(text1h);
H(7,8)=handles.edit8*handles.edit24/(text1h);
H(8,8)=handles.edit8*handles.edit25/(text1h);
H(9,8)=handles.edit8*handles.edit26/(text1h);
H(10,8)=handles.edit8*handles.edit27/(text1h);
H(11,8)=handles.edit8*handles.edit28/(text1h);
H(1,11)=handles.edit9*handles.edit18/(text1h);
H(2,11)=handles.edit9*handles.edit19/(text1h);
H(3,11)=handles.edit9*handles.edit20/(text1h);
H(4,11)=handles.edit9*handles.edit21/(text1h);
H(5,11)=handles.edit9*handles.edit22/(text1h);
H(6,11)=handles.edit9*handles.edit23/(text1h);
H(7,11)=handles.edit9*handles.edit24/(text1h);
H(8,11)=handles.edit9*handles.edit25/(text1h);
H(9,11)=handles.edit9*handles.edit26/(text1h);
H(10,11)=handles.edit9*handles.edit27/(text1h);
H(11,11)=handles.edit9*handles.edit28/(text1h);
set(handles.H,'Data', H);
% cylinder heat transfer
H(1,9)=handles.edit8*handles.edit18/(text2h);
H(2,9)=handles.edit8*handles.edit19/(text2h);
H(3,9)=handles.edit8*handles.edit20/(text2h);
H(4,9)=handles.edit8*handles.edit21/(text2h);
H(5,9)=handles.edit8*handles.edit22/(text2h);
H(6,9)=handles.edit8*handles.edit23/(text2h);
H(7,9)=handles.edit8*handles.edit24/(text2h);
H(8,9)=handles.edit8*handles.edit25/(text2h);
H(9,9)=handles.edit8*handles.edit26/(text2h);
H(10,9)=handles.edit8*handles.edit27/(text2h);
H(11,9)=handles.edit8*handles.edit28/(text2h);
H(1,12)=handles.edit9*handles.edit18/(text2h);
H(2,12)=handles.edit9*handles.edit19/(text2h);
H(3,12)=handles.edit9*handles.edit20/(text2h);
H(4,12)=handles.edit9*handles.edit21/(text2h);
H(5,12)=handles.edit9*handles.edit22/(text2h);
H(6,12)=handles.edit9*handles.edit23/(text2h);

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H(7,12)=handles.edit9*handles.edit24/(text2h);
H(8,12)=handles.edit9*handles.edit25/(text2h);
H(9,12)=handles.edit9*handles.edit26/(text2h);
H(10,12)=handles.edit9*handles.edit27/(text2h);
H(11,12)=handles.edit9*handles.edit28/(text2h);
set(handles.H,'Data', H);
% spherical heat transfer
H(1,10)=handles.edit8*handles.edit18/(text3h);
H(2,10)=handles.edit8*handles.edit19/(text3h);
H(3,10)=handles.edit8*handles.edit20/(text3h);
H(4,10)=handles.edit8*handles.edit21/(text3h);
H(5,10)=handles.edit8*handles.edit22/(text3h);
H(6,10)=handles.edit8*handles.edit23/(text3h);
H(7,10)=handles.edit8*handles.edit24/(text3h);
H(8,10)=handles.edit8*handles.edit25/(text3h);
H(9,10)=handles.edit8*handles.edit26/(text3h);
H(10,10)=handles.edit8*handles.edit27/(text3h);
H(11,10)=handles.edit8*handles.edit28/(text3h);
H(1,13)=handles.edit9*handles.edit18/(text3h);
H(2,13)=handles.edit9*handles.edit19/(text3h);
H(3,13)=handles.edit9*handles.edit20/(text3h);
H(4,13)=handles.edit9*handles.edit21/(text3h);
H(5,13)=handles.edit9*handles.edit22/(text3h);
H(6,13)=handles.edit9*handles.edit23/(text3h);
H(7,13)=handles.edit9*handles.edit24/(text3h);
H(8,13)=handles.edit9*handles.edit25/(text3h);
H(9,13)=handles.edit9*handles.edit26/(text3h);
H(10,13)=handles.edit9*handles.edit27/(text3h);
H(11,13)=handles.edit9*handles.edit28/(text3h);
set(handles.H,'Data', H);

% --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% this call on temperature FDM figure file
open heat3.fig

```