

Technological Developments in Annealing Furnaces for Performance Improvement

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Abstract

Today the requirement of annealing furnaces is increasing for the heat treatment processes of various mechanical products such as sheet metal, wires, gears, etc. Heat treatment process is very important step in manufacturing industries for which furnaces are developed over a period of time with continuous innovations. The study of these furnaces becomes necessary for producing revampments or innovations for development in this field. Over the years variety annealing furnaces have been developed working on different principles. Out of these, the furnace operating on electric resistance heating is found to be most efficient and cost effective. The incorporation of unsteady state concept while designing the furnace has become important which brings real time parameters in to consideration for better working and output of furnaces.

Keywords: Annealing Furnace, Innovations, Electric resistance heating, Efficient, Unsteady state Lumped heat capacity

Introduction

An annealing furnace is used to transform or restore metallurgical properties in a temperature controlled environment, allowing the strength and hardness properties of these materials and internal stresses to be changed. When the form or shape of any metal item is changed as part of a manufacturing process, this will usually alter its underlying metallurgy, through work hardening, for example drawing and rolling process. Annealing furnaces are used sequentially in such manufacturing processes, to restore or further change the metal's properties in order to achieve the desired end-results for the product concerned. As a result of this they come in a wide variety of sizes and are capable of different functions and temperatures. Continuous annealing furnaces perform annealing by continuous methods in which flow of material is continuous. This type of furnace is generally used for annealing the wires and strips.

The annealing process of different alloys has traditionally been a challenge. Many technical difficulties prevented inline annealing, forcing the producers to batch anneal the strips in furnaces. This added step in the complete process resulted in productivity losses, longer lead times and increased processing costs. Recent advances in annealing furnaces processing technology have opened a new door. It is now possible to anneal strips using the furnaces which operate in batch, continuous and different source of heat.

Methodology of Annealing Process

Several annealing methods for wires are used in practice. In principle, they can be divided into two categories:

1. Batch annealing or tempering methods in which strips are annealed in different furnaces such as bell, salt bath, roller grate, muffle, etc. The transferring of heat takes place by radiation and/or convection. The batch annealing or tempering methods are characterized by long heating periods as it takes a long time to obtain an even temperature in massive spools. A further disadvantage is the possible sticking together of the loops of strips because of the long annealing period and the high temperature. In addition, the degree of purity of the wires may remain unsatisfactory after the annealing.

2. Annealing by continuous methods in which strips are conveyed through a pipe heated from the outside or in which wires are heated directly either inductively or resistively. When annealing is carried out by continuous methods in a through-type furnace, the annealing capacity remains low because of the slow movement of the strips, which is the reason why the method is expensive. If the annealing capacity is increased either by lengthening the furnace or by increasing the number of wires to be drawn through it, the furnace becomes very impractical structurally.

Study of Annealing Furnaces

3.1. Gas Fired Radiation Furnace for Annealing

In a wire drawing plant, annealing is a key part. This improves workability of the material during drawing process. The process of annealing is done in a furnace, which is fired in some of the cases of the cluster by wood for annealing MS wire and electricity by others annealing copper or aluminum. Traditionally for annealing copper or aluminum, electric furnaces has been used because of the need of precision control of temperature over time and clean environment to avoid contamination of the copper/aluminum wire to be drawn. The electric furnaces in the units typically use nichrome coils weighing 1 kg to 1.25 kg, twelve in numbers giving a total rating of 66 kW electrical heating capacity of the furnace and consumed about 99600 kWh per year out of the 295310 kWh per year for the entire unit (i.e. a share of 8.14 *lakh* out of a total of 24.13 *lakh*). Thus these furnaces use a very costly fuel and the expenditure towards fuel can be reduced by as much as 15-20% upon replacing with gas fired radiation furnaces.

Recently technological breakthrough has made it possible to meet both the ends even with the use of LPG or natural gas in specially designed furnaces. The main shell of the oven would be rectangular in shape, fabricated out of rolled Mild Steel sheets duly reinforced with adequate structural rolled steel for rigidity and sturdy construction. The baffle of the furnace shall be fabricated from SS-310 material. The furnace would be lined with ceramic wool blankets of suitable density to minimize the heat loss. It is proposed to install two nos. RAD-HEAT Gas Heating Elements using LPG/NG in the furnace. The total heating load of the elements shall be 80 kW and will be fully automated to control the temperature in a clean environment. The elements shall be made out from SS-310 material to ensure long life and radiation heating. All necessary and possible measures would be taken to minimize the heat loss. Using gas fired radiation furnace would save high grade energy more than 99600 kWh of electricity over a year. The quality of the product would still remain the same. It shall have no impact on the annealing process but merely make it more efficient. [1]

3.2. Bell Annealing

Bell Annealing is a type of annealing that derives its name from the shape of the furnace used during the process. Bell Annealing heats batches of metal which are placed on a base assembly, enclosed by an inner cover, and covered by the furnace. An overhead crane is used to load the base and move the equipment—when the furnace is suspended from the crane, it looks like a —bell. The base assembly is the source of convection and the main method of heat transfer to the charge. The

inner cover seals in the desired atmosphere and protects the charge from the burners' direct heat. Keeping contaminants out of the annealing atmosphere prevents chemical changes as well as eliminating the formation of oxides and soot on the metal. The furnace brings the charge to the desired temperature to allow for the metallurgical changes to occur. Direct fired, tangentially fired, radiant tube, and electrical resistance are furnace types related to the method used to heat the charge. After heat treatment, cooling is performed by removing the furnace - leaving the inner cover in place to maintain the protective atmosphere. If a bright finish is desired, the metal must be cooled to near ambient temperature before exposing the metal to air. In this case, another piece of equipments utilized: a forced-cooler. The forced-cooler replaces the furnace at the end of the heating cycle and uses air and sometimes spray water to accelerate the cooling of the outside of the inner cover [2].

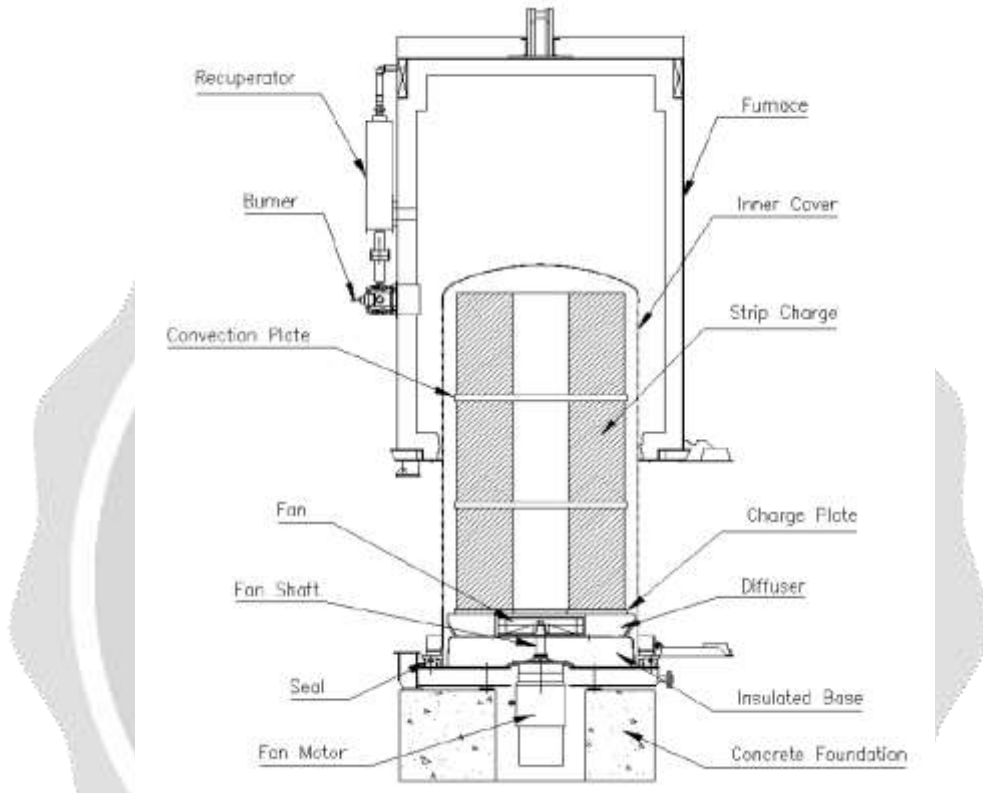


Fig. 1 Super-High Convection™ Bell Annealing Furnace for Strip Coils [2]

The main advantages of a Bell-Type annealing furnace are:

- i. Excellent temperature uniformity
- ii. Consistent product quality
- iii. Good production rates
- iv. Low operating costs
- v. Efficient use of furnace asset by cooling with inner cover
- vi. Savings in shop floor space requiring less capital investment and reducing material handling.

3.3. Uniflow Annealing System (UAS) furnace

During steel manufacture, the process of cold rolling introduces stresses due to changes in the crystalline structure of the metal. These stresses are released by further heat treatment (annealing) which reforms the crystalline structure and reintroduces desirable mechanical properties. The steel for this stage is in the form of a coil. The coil has been produced by

wrapping a long steel sheet about an armature, which is then removed, leaving a curved inner surface. The entire steel coil has to be raised to a specified temperature within a Uniflow Annealing System (UAS) furnace. The steel coil is then maintained at this temperature for a period of time to achieve annealing. New Zealand Steel has a number of formulae that they use to decide how long to keep a set of coils in the furnace, to ensure the thermal centre of each coil reaches the desired temperature. These formulae were derived from data generated during commissioning of the furnace, and subsequently lost. The formulae have also been modified over the years, and the original formulae are no longer available.

To predict existing heating equations accurately heating times based on coil weight and width and the need to factor strip thickness into the heating equations, for that we need to model the heat transfer from the furnace through the steel coils. It required modeling on

- i. Heat transport within the coils
- ii. Radial Conductivity — Modeling the Gaps
- iii. Estimates of heating times
- iv. Linear heat transfer — analytic solutions

The analytical and numerical investigations suggest that, with the boundary conditions chosen here, the main constriction on the heating of the steel coils is the slow transport of heat through the curved sides of the coils. Further analytical and numerical investigations with radiative heating of all the outer surfaces show a considerable reduction in the heating times.

It is difficult without further experimental data to assess the validity of our assumed boundary conditions. We have ignored the effect of the location of the coil in the furnace but industrial experience suggests that failure of the annealing process is associated with particular grid positions within the furnace. There will be further radiation within the furnace such as between the sides of the steel coils. Studying the plan of the roof of the furnace further suggests that some parts of the circular top ends of the coils could be partially shielded from the radiation from above, which would break the cylindrical symmetry which we have assumed.[3]

3.4. Continuous Annealing Heating Furnace

Fig. 2 shows a typical continuous annealing process called C.A.P.L. (continuous annealing and processing line). Here, the material for annealing is a cold-rolled strip coil, which is put on a pay-off reel on the entry side of the line. The head end of the coil is then pulled out and welded with the tail end of the preceding coil. Then the strip runs through the process with a certain line speed. On the delivery side, the strip is cut into a product length by a shear machine and coiled again by a tension reel.

The heat pattern of the strip, as shown in Fig. 3, is determined according to the composition and the product grade of the strip. The actual strip temperature must be within the defined ranges from the heat pattern to prevent quality degradation. The value of the heat pattern at the outlet of the heating furnace is the reference temperature for the control. In most cases, the strip in the heating furnace is heated indirectly with gas-fired radiant tubes.

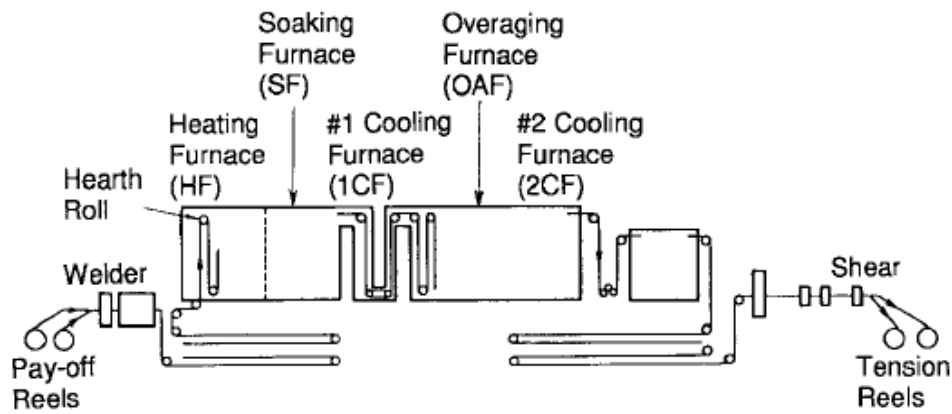


Fig. 2 Outline of a continuous annealing process [3].

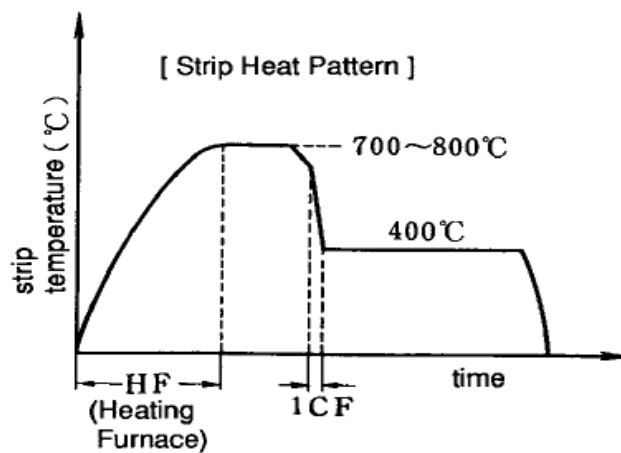


Fig. 3 Strip heat pattern for continuous annealing [3].

Fig. 4 schematically illustrates the control system. The system, installed in a process control computer, is hierarchically structured. It consists of “optimal preview control” at a higher level, and “strip temperature tracking control” and “parameter estimation” at a lower level.

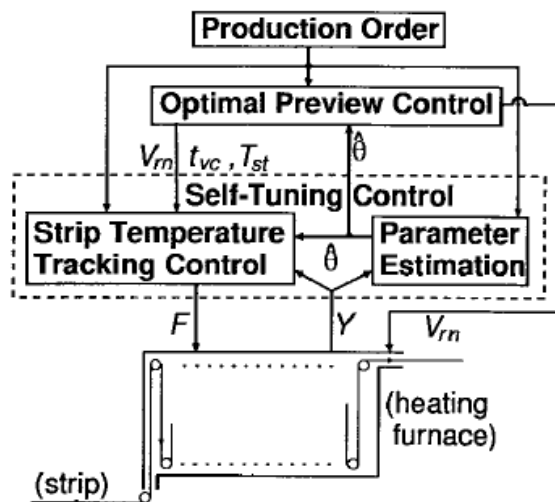


Fig. 4 Diagram of strip temperature control system [3].

A simplified mathematical model is derived from first principles. The model parameters are recursively estimated with

an algorithm called recursive parameter estimation with a vector-type variable forgetting factor (REVVF). The REVVF algorithm was developed for such cases where some knowledge on parameter variability can be obtained beforehand. The control system of strip temperature presented here is hierarchical. The upper level is called “optimal preview control,” which performs preset control. It previews the approaching setup change, which is the change of strip size or reference temperature, and optimizes the line speed and the strip temperature trajectory. Next, the lower level is called “temperature tracking control,” which performs closed-loop control using the above trajectory as the control target. At this level, the generalized pole-placement self-tuning control was first employed; and later, the generalized predictive self-tuning control was introduced. These control methods were applied with some practical modifications and with the above mentioned REVVF. The control has been working successfully in several real plants.

The strip temperature control at the heating furnace in continuous annealing processes has been developed using self-tuning control schemes. The control has the following important features.

- i. Plant model: Both dynamic and static models are developed and used in the control. The dynamic model of strip temperature includes the static model for forming disturbance terms and for gain scheduling, to increase model accuracy.
- ii. Optimal preview control: In order to take control actions well before a setup change, the speed reference, the optimal timing of speed change and the optimal temperature trajectory (target trajectory) are calculated for the approaching setup change.

Temperature tracking control: GPP-STC or GP-STC is employed for the control to cope with sluggish, non minimum phase and slowly time-varying characteristics of the plant. In GP-STC, the cost function is modified to prevent overheating of the furnace. [3]

3.5. Diesel Fired Furnace

Heat treatment furnaces with effective temperature sensing, heat retaining capacity and controlled environment are necessary for heat-treatment operations to be successfully performed. Some of the processes require heating cycles for durations spanning a few minutes to several hours depending of the material and the properties desired. The absence of constant power supply in the country has made it difficult for a wide range of heat-treatment operations to be effectively performed. This challenge is the motivation for this research aimed at the development of a portable heat-treating furnace that relies on diesel to fire and generate the heat needed to raise the temperature of the furnace to the desired level. The elimination of the use of heating elements which requires electric power to function is the fundamental design principle justifying the research work.

The casing is first positioned and lined with refractory up to 100mm thickness on the sides and 200mm at the floor and plastered with a mixture of kaolin and clay with binder. The pot is then placed in the casing and held by refractory at the flanges leaving a combustion zone of 50mm round the pot and 100mm between the base of the pot and the flooring.

The casing, inner pot, and the refractory are left for days to dry. The refractory shrinks due to loss of water thereby opening up some gaps. These breaches are then repaired using more refractory mixture to plaster. This process is done to prevent explosion or loss of heat due to improper refractory moulding and support. The furnace cover and job holder are also fixed. The exhaust pipe is then fitted. The casing is designed such that the exhaust hole protrudes outward preventing heat concentration at the exit which can damage the furnace. The protruded length is about 100mm being 2mm smaller the dimension of the inner cross section of the exhaust pipe. This is to aid the unidirectional flow of heat and smoke out of the chamber through convection. Next is the burner. It is placed in the hole at an angle of 45° on the horizontal plane below the

exhaust. The position is to allow for homogenous and enough heat residential time in the burning chamber before heat exit through the exhaust. The burner is placed in such a way that the flame is directed to the bottom of the pot at some distance away from it. With this setting the temperature in the burning zone could be as high as 11000C in the burning chamber and 900- 1000°C in the inner pot.

The electro-technical devices are then connected for the automation of the furnace system. This involves the connection of the thermocouple through the thermocouple lead to the temperature controller. The controller switches on and off the burner as the set temperature is reached. This controller box is joined to the furnace but separated with few centimeters to avoid heating the temperature controller devices. The controller box is tilted 300 to the vertical for easy viewing even while standing. The furnace is switched on via an industrial switch and the working progress indicated by LED indicator light.

The design philosophy is to eliminate the use of heating elements requiring electric power which is poorly supplied in the country. Design drawings were produced and mild steel was used for the fabrication of the furnace casing, while the other components needed for the design were selected based on functionality, durability, cost and local availability. The furnace was assembled by lining the inner wall of the casing with refractory blocks made from heated mixture of kaolin, clay, sawdust and water after which the inner pot and electro technical devices (temperature controller, light indicator etc.) were positioned. Testing was subsequently performed to evaluate the performance of the furnace. It was observed that the furnace has a fast heating rate (61.24°C/min to attain a pre-set temperature of 900°C); and a fuel consumption rate less than 1.41 liters/hr. It was also observed that the furnace has good heat retaining capacity; can be easily maintained and safe for use. [4]

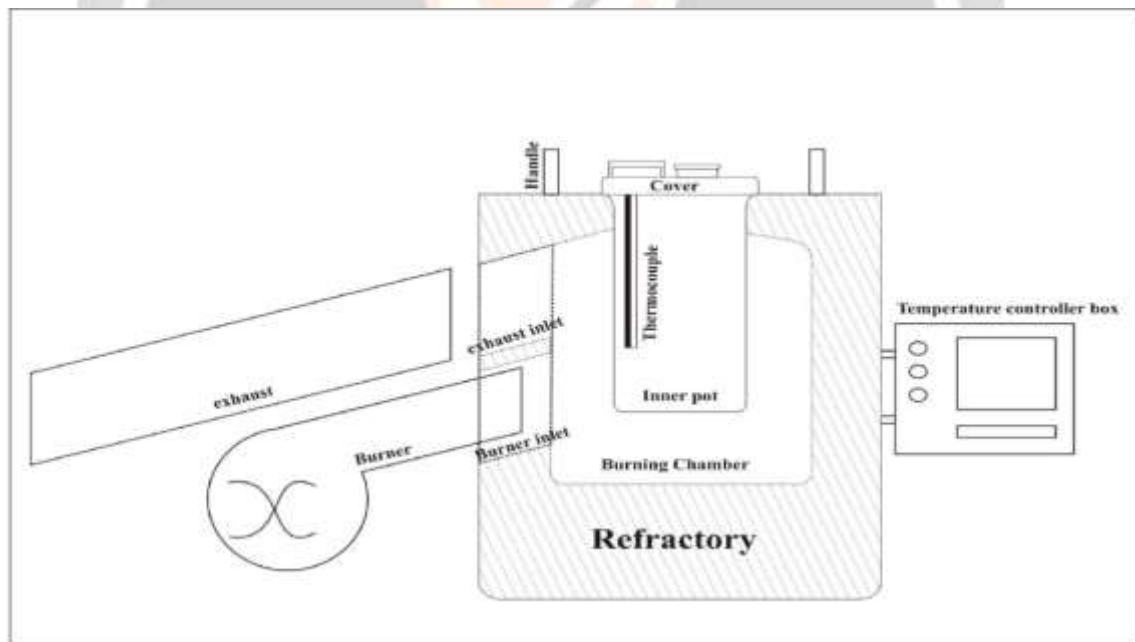


Fig. 5 A cross section of the design of the furnace showing all critical units [4].

3.6. Energy, Exergy and Economic Analysis of an Annealing Furnace

Heat balance analysis based on the first law of thermodynamics is the primary method to analyze energy use characteristics in the furnace. This method is used to analyze the situation of energy use and evaluate integrity of systems or equipments according to the conservation of energy principle, which may be expressed as follows: The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process. A furnace can be divided into two parts; combustor chamber and annealing chamber as shown in Figure 3.

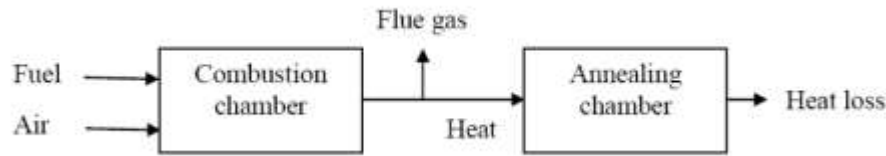


Fig. 6 Schematic diagram of combustion and annealing chamber of a furnace [6]

The useful concept of energy and exergy utilization is analyzed to investigate the energy and exergy efficiencies, energy and exergy losses, energy savings and cost benefit of an annealing furnace. The energy and exergy efficiencies of combustor and annealing chamber of the furnace have been analyzed as well. The energy and exergy efficiencies of combustor and annealing chamber of the furnace have been analyzed as well. The exergy efficiency of the combustor is found to be 47.1%. The energy and exergy efficiencies of the annealing chamber are found to be 17.7 and 12.9% respectively. The overall energy and exergy efficiencies of the furnace are found to be 16.7 and 7.3% respectively. It is found that the annealing chamber is the major contributor for exergy destruction of about 57% followed by combustion chamber of the annealing furnace. By using a heat recovery system from the flue gas, about 8.1% of fuel can be saved within the payback period of less than 2 months. By using the heat recovery system, about 113.8 MJ/h can be recovered with the payback period of less than 2 months. [6]

3.7. Electric Annealing Furnace

A simple, portable, and electromagnetically regulated annealing furnace was successfully fabricated for improving the microstructure and mechanical properties of materials by removal of crystal defects and internal stresses. The oven was fabricated using locally available materials in Nigeria such as fiberglass, nichrome element, and magnetic temperature controller.

The annealing furnace has outer cover covering of dimensions of 35x28x30cm and inner dimensions of 28x20x22cm. The fiberglass was used in-between the outer and inner metal pans as an insulating material to prevent heat losses by conduction and convection. The door was perfectly sealed and with an insulating handle. The magnetic temperature controller was attached to the top of the furnace and is detachable. The temperature controller allows for the furnace temperature to be controlled to any desired point between 0-400°C. The furnace provides only for annealing of materials in air. It can be modified for other gas environment and vacuum annealing.

The oven is an adiabatic system with the dimensions of 35x28x30cm. It is powered by 240V, 1,100W nichrome heating element. The special feature of the furnace is an electromagnetic temperature controller which regulates the annealing temperatures. The furnace generates heat at the rate of $1,035.25\text{Wm}^{-2}$ with the high efficiency of 94%. Among other purposes, the furnace is found very useful in annealing materials (as-deposited crystals) at desired temperatures. [7]

3.8. Unsteady State Continuous Annealing Furnace

This type of furnace considers all the unsteady state parameters during its design. A lumped heat capacity analysis is done to evaluate the heat transfer over the time period. Fig. 7 shows the developed annealing furnace. It consists of Alumina refractory tube of size 60mm × 50mm and 1.3m length. Kanthal wire is used as heating element because it have high longer life also longer life also higher maximum operating temperature 1425°C than that of the Nickel-Chromium. It is wounded around the periphery of the refractory tube Ceramic fiber is used as insulation which is wounded around the periphery of refractory tube on heating element. It is better insulator up to 1500°C because lower thermal conductivity, light weight and lower heat capacity. The temperature controller allows for the furnace temperature to be controlled to any desired point

between 0-1000°C as sensed by k type thermocouple. The furnace provides only for annealing of wire in air. Two DC motor and pulley are used to pull the wire through refractory tube. Pulley is mounted at end of motor shaft which pulls the wire and pushes it through tube furnace to other end.

The annealing time is determined by lumped heat capacity system which gives accurate, real time, transient analysis of the factors required for annealing. [8]



Fig. 7 The actual setup of developed Unsteady State Continuous Annealing Furnace [8]

3.9. Other Developments

An electric arc furnace is designed and constructed to melt approximately 5 kg of steel/cast iron scraps, using locally produced Soderberg electrodes. Test carried out which showed that it required about 60 minutes to heat up the furnace to the melting temperature of cast iron (1150°C – 1400°C). It took about 95 minutes to melt the first charge of 2 kg resulting in a melting rate of 21.05 g/minute. The average electrode consumption rate was 0.0467 cm/minute. A transformer efficiency of about 83% was also achieved (Oyawale F. A. et al., 2007).

The furnace (Alaneme K. K. et al., 2010) assembled by lining the inner wall of the casing with refractory blocks made from heated mixture of kaolin, clay, sawdust and water after which the inner pot and electro technical devices (temperature controller, light indicator etc.) were positioned. Testing was subsequently performed to evaluate the performance of the furnace. It was observed that the furnace has a fast heating rate (61.24°C/min to attain a pre-set temperature of 900°C); and a fuel consumption rate less than 1.41 liters/hr. It was also observed that the furnace has good heat retaining capacity; can be easily maintained and safe for use.

The useful concept of energy and exergy utilization is analyzed to investigate the energy and exergy efficiencies, energy and exergy losses, energy savings and cost benefit of an annealing furnace (Hasanuzzaman M. et al., 2011). The energy and exergy efficiencies of combustor and annealing chamber of the furnace have been analyzed as well. The energy and exergy efficiencies of combustor and annealing chamber of the furnace have been analyzed as well. The exergy efficiency of the combustor is found to be 47.1%. The energy and exergy efficiencies of the annealing chamber are found to be 17.7 and 12.9% respectively. The overall energy and exergy efficiencies of the furnace are found to be 16.7 and 7.3% respectively.

A simple, portable, and electromagnetically regulated annealing furnace was successfully fabricated for improving the

microstructure and mechanical properties of materials by removal of crystal defects and internal stresses (Offor P. O. et al., 2009). The oven was fabricated using locally available materials in Nigeria such as fiberglass, nichrome element, and magnetic temperature controller. The oven is an adiabatic system with the dimensions of 35x28x30cm. It is powered by 240V, 1,100W nichrome heating element. The special feature of the furnace is an electromagnetic temperature controller which regulates the annealing temperatures. The furnace generates heat at the rate of $1,035.25\text{Wm}^{-2}$ with the high efficiency of 94%. Among other purposes, the furnace is found very useful in annealing materials (as-deposited crystals) at desired temperatures.

The computer package developed was designed to analyze the energy distribution with effective heater material selection in the manufacture of electric furnace. The computer analysis was for both rectangular and cylindrical heating element, which give optimum performance in terms of operation. The design was for furnace with temperatures not exceeding 1000°C based on the available electric voltage and power. The design also specifies the advantage of cylindrical heater type over the rectangular type in terms of its effectiveness and quick response to temperature distribution and attainment within reasonable time limit (Ajiboye K., 2004).

Wire running through contact wheels is resistance heated by a current set to heat the wire in a first step to a relatively low temperature which has been determined experimentally and which is dependent upon, e.g., the drawing rate, the protective gas used, cooling, the thickness of the wire, the length of the annealing distances, and the solidus temperature of the wire to create a controlled number of crystal nuclei in the wire and then the actual annealing is effected in a second step by a current heating the wire to a high temperature to re-crystallize the wire completely (Kosonen A. A. et al., 1973).

The paper (Yoshitani N. et al., 1998) presents the model of the heating furnace in continuous annealing processes for use in design of self-tuning control systems. A simplified mathematical model is derived from first principles. The model parameters are recursively estimated with an algorithm called recursive parameter estimation with a vector-type variable forgetting factor (REVVFF).

Discussion

From the number of studies regarding annealing furnaces it can be said that the furnaces working on the input energy like gas, diesel, etc. have number of disadvantages like uncontrolled fire is produced by burning the fuel with uncontrollable temperatures. Moreover, the combustion products formed such as carbon dioxide, carbon mono-oxide, sulphur, etc, get embedded in the product to be annealed and further cause the doping of impurities in to it.

The crucible furnaces operating on electric resistance heating are more energy efficient than that of the conventional wood-fired or fuel-fired furnaces. The electric furnaces are operating on clean source of energy which reduces pollution caused due to the fuel fired furnaces and minimizes defects drastically than in earlier ones. Also less net input energy required is less increasing the thermal efficiency of the system and reducing the operating cost as well as time (Bureau of Energy Efficiency of India (BEE)).

A clean source of energy is to be utilized to generate the heat required for annealing so that there is optimization in use of energy. This will also ensure the better product quality and enhance the thermo-physical properties of the annealed product. The development, innovations or revampments can be brought upon in such furnaces to eradicate the existing disadvantages and improve the performance of furnaces by implying the ideas of continuous process of annealing instead of batch annealing, use of clean source of energy and many more.

Tests were carried out by Kumbhar S. V. et al. [8], at supply of 230 V, 2650 W kanthal heating element. The result shows that it required about 30 minutes to heat up the furnace to the annealing point of aluminium (200°C to 250°C). The

temperature of the furnace increases at the rate $67^{\circ}\text{C}/\text{min}$. (Fig. 5) which is at a better rate than in the furnace (Alaneme K. K. et al., 2010) having $61.24^{\circ}\text{C}/\text{min}$ heating rate. It is observed that it requires 30 minutes to reach at temperature of about 300°C which is slower than 18 minutes to reach similar temperature (Offor P. O. et al., 2009). This is due the convective heat losses from side openings at a very high rate of $40\text{ W}/\text{m}^2\text{ K}$. The furnace generates heat at the rate $1035\text{ W}/\text{m}^2$ (Offor P. O. et al., 2009) while that of our developed furnace generates $2650\text{ W}/\text{m}^2$ given that there are quite a bit of heat losses. This decreases the thermal efficiency of the furnace by about 3-5% depending on heat transfer coefficient. The result shows that it required about 30 minutes to heat up the furnace to the annealing point of aluminium (200°C to 250°C). The temperature of the furnace increases at the rate $67^{\circ}\text{C}/\text{min}$. (Fig. 8)

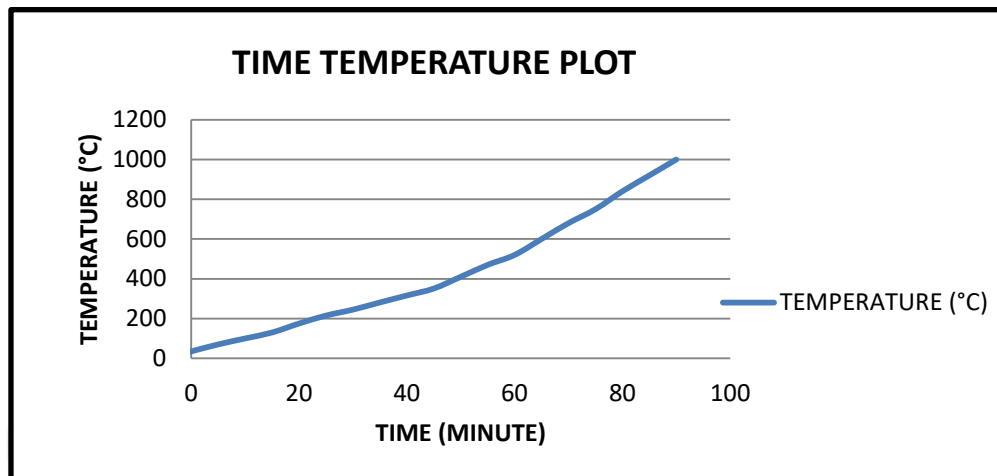


Fig. 8 Time-Temperature plot of developed Unsteady State Continuous Annealing Furnace [8]

Conclusions

The development of annealing furnaces has brought upon the incorporation of unsteady state lumped heat system which gives a new dimension to the working of furnaces. The efficiency has improved quite drastically while continuously operating the furnaces which have made them both cost and time effective. Moreover, a clean source of energy is utilized to generate the heat required for annealing and also there is optimization in use of energy. The chances of embedment of combustion products like carbon, sulphur, CO_x , NO_x , etc. are eliminated which would rather tend to alter the composition of annealed product on its surface. This will also ensure the better product quality and enhance the thermo-physical properties of the annealed product.

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