Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013), Cranfield University, UK, 19th – 20th September 2013, pp 263-268

A NOVEL METHODOLOGY TO ASCERTAIN THE HEATING MECHANISM OF STEEL WIRE DURING ANNEALING IN A TUBE FURNACE

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ABSTRACT

The paper describes a methodology to determine the heating mechanism of steel wire inside a tube furnace used for annealing. The approach is based on Lumped Heat Capacity method of heating where the 'surface heat transfer coefficient' is obtained from radiation considerations. The developed methodology calculates the temperature of the wire as it travels along the tube furnace whose surface temperature is kept at about 800 ^{o}C. The results obtained from the developed methodology have been compared with experimental data and the possible reasons for the discrepancies identified. The influence of surface emissivity and its consequence on the heating rate has also been documented. The approach highlights that the method may serve as a useful tool to predict temperatures for this kind of furnace in order to optimize the manufacturing process.

Keywords: annealing, heat transfer, lumped heat capacity.

1 INTRODUCTION

To relieve stresses from cold drawing and to regain ductility, steel wires are annealed in furnaces at appropriate temperatures. The process of annealing is usually accomplished by two methods, either by allowing big coils of steel wires to 'soak' in a controlled furnace environment known as batch annealing (Mehta, 2009) or by continuously feeding the cold-rolled wire through tube furnaces at a controlled speed (Hasan et al, 2012). Prolonged exposure at high temperature accelerates the stress relief and crystal alignment processes such that the final product regains the correct properties for further rolling or for delivery to the customer. In order to ensure a good surface quality, the environment inside the heated furnace is maintained by various non-oxidising gases such as hydrogen or nitrogen (Herring, 2010). In the case of a tube furnace, which is the main concern in this work, the steel wires are fed through a fairly long heated tube maintained at a specified temperature followed by a long cooling section. Figure 1 illustrates the whole rig divided into furnace and two cooling sections and Figure 2 shows a typical temperature distribution of the steel wire as it passes along the rig.

Typically there will be three zones of wire inside the furnace as far as the wire temperature is concerned: the heating zone (increasing temperature), 'soaking zone' (of fairly uniform temperature) and cooling zone (decreasing temperature). In order for the metal crystals to align and for the steel wire to regain the expected yield strength, the soaking zone should be of sufficient duration. When the wire comes out of the tube furnace, a small sample of the wire is checked for tensile strength and hardness. If the required strengths are not met, then the wires are passed through additional annealing operations making the process less efficient and more expensive. A typical wire drawing is completed in several steps of alternate cold drawing and annealing processes in a series and is very time consuming.

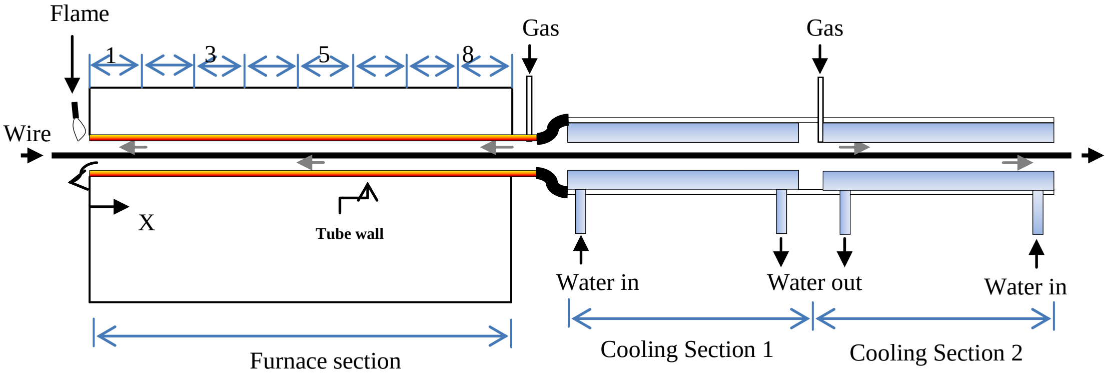

Figure 1: Schematic of an annealing rig for drawing steel wire

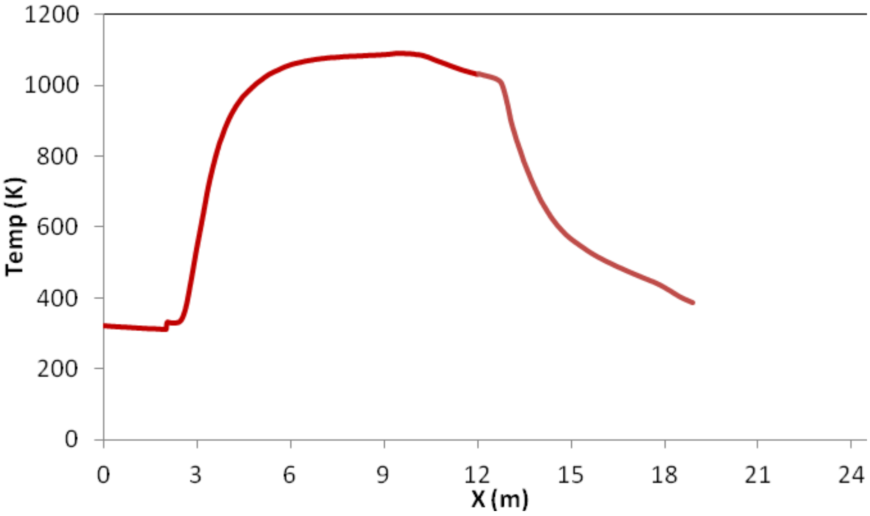

Figure 2: Typical temperature variation of the wire

Clearly, a faulty annealing disrupts the flow of material and means extra work to set new annealing parameters. The net effect means a loss of productivity. The process of tube furnace annealing has evolved essentially by trial and error and rigorous scientific literature on this type of furnace is very limited. On the other hand, batch annealing is suitable for very large production rate, and a considerable attention has been given to these processes and as such a rich volume of literature exists (Mehta, 2009; Perrin *et.al* 1988). To highlight the focus of the present work, few relevant issues that came out of the literature are briefly discussed in the next paragraph.

The process of annealing is dependent on the heat transfer from the furnace wall to the core of the wire by radiation and convection through the gases. In the case of batch annealing where the wires are wound in layers, the heat transfer process is further complicated due to thermal contact resistance and air voids. Zuo et al (2001) have reported work on the heat transfer for High Performance Hydrogen Bell type furnace and have noted the importance of surface heat transfer coefficient. Regarding the use of reducing gases, the general findings suggest that the use of hydrogen is more efficient due to its higher thermal conductivity than nitrogen. However, hydrogen is more hazardous and hence the installations are likely to be more expensive. An important difference between batch annealing and tube furnace annealing is that the latter has a much higher gas flow rate (Herring, 2010). This also highlights the importance of the fluid dynamics involved in the process. From design considerations, the items of significance are the diameter of the tube, type of gaseous atmosphere, flow rate of gas used, speed of wire and the quality of heating surface. Since the designs have essentially evolved by trial and error, the fundamental thermo-fluidic mechanism is not very well understood. For example, although the heat transfer is known to be largely by radiation, the relative contribution by radiation and convection are not unclear. An important aspect is the temperature variation within the wire during the heating and cooling lengths.

In this paper a method based on fundamental heat transfer mechanism has been proposed which can act as a tool to predict the heating rate of the steel wire. Some experimental data were collected for steel wire as it passed through the furnace and these data were used for validation. The limitations of the proposed method are also critically discussed.

2 METHODOLOGY

2.1 Experimental Approach

Temperature along the whole length of the annealing rig was obtained by using high temperature thermocouple wires. The junction of the thermocouple was embedded inside a section of a 5 mm stainless steel wire as shown in Figure 3. Temperature readings were recorded by a logger by varying the speed (1 m/min and 2 m/min) and gas compositions of H_2 and N_2. Since the objective of this paper is to concentrate on the theoretical technique, the detailed experimental data are excluded from this paper but will be made available in future. Only one specific case for 100% N_2 and 2 m/min condition is considered for validating the present analytical method.

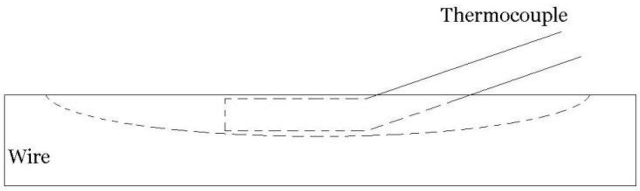

Figure 3: Embedded thermocouple inside the wire

2.2 Analytical Approach

The method is based on the concept of 'Lumped Heat Capacity' which is valid for transient heating of convection-conduction system under certain conditions (Holman, 2009). This 'Lumped Heat Capacity' is based on the fact that the heat gain in a solid of mass Δm (=ρC_p) is equal to the net heat transfer through the surface area.

$$h(T_\infty - T)A_s = \rho c_p \frac{\partial T}{\partial t} V \qquad (1)$$

Assuming that the steel wire is split into small lumps (1, 2, 3 etc) as shown in Figure 4, we assume that the heating of each element follows Equation 1 above such that any heat coming from the furnace wall is contributing to the heating of the element through the surface of area, A_s.

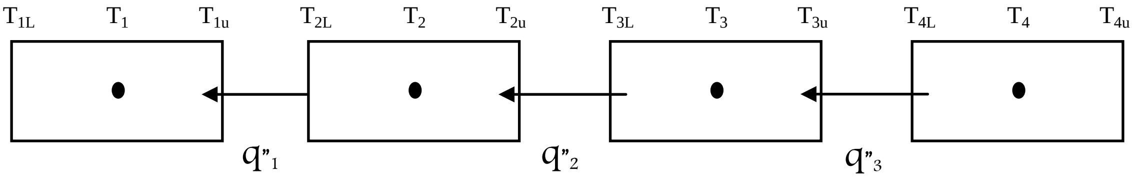

Figure 4: Schematic illustration of the steel wire segments representing the lumps

The symbols used above and their meaning in the current context are given below.

Table 1: Interpretation of symbols in the present context

Symbol	Meaning for lumped heat capacity	Interpretation for the present case
T_∞	Surrounding temperature	Surface temperature of tube wall
T	Temperature of ‘lump’	Temperature of wire ‘segment’
A_s/V	Surface area/Volume ratio of lump	Surface area/Volume ratio of segment
ρ, C_p	Density, Specific heat of material	Density, Specific heat of stainless steel
T	Time	Time
H	Surface heat transfer coefficient (convection)	Surface heat transfer coefficient (radiation)

The solution to the above first order differential equation is given below:

$$T(t) = T_\infty + (T_0 - T_\infty)e^{\frac{-h A_s}{\rho c_p V}t} \tag{2}$$

In general, three modes of heat transfer needs to be considered. The conduction component is included in the analysis via q_1”, q_2” etc. due to temperature gradients ($T_{1u} < T_{2L}$) as shown in Figure 4 above which is calculated by Fourier’s conduction law given below.

$$q = kA\frac{\Delta T}{dx} \tag{3}$$

The convection component has been found to be negligibly small as reported in our earlier paper (Hasan et al., 2012). The main feature of the present work is that we consider the radiation heat transfer from the tube wall to the steel wire via a radiation surface heat transfer coefficient, h_r which is given by Equation [4].

$$h_r = \frac{\sigma\left(T_1^2 + T_2^2\right)(T_1 + T_2)}{1/[\varepsilon_1 + (A_1/A_2)(1/(\varepsilon_2 - 1))]} \tag{4}$$

In the above expression, A stands for the surface area and ε stands for the emissivity; the subscripts 1 and 2 represent the steel wire and tube wall surface respectively. The h_r replaces h in Equation [2].

With reference to Figure 4, the temperature T_1 of segment 1 at the first time step is calculated via Equation [2], where T_o is the initial temperature of the wire as it enters into the furnace. At the second time step, when the segment has moved to the next position, temperature T_2 is obtained by reference to T_1 which acts as the initial temperature. The whole process is very similar to the time marching technique used in CFD (Versteeg, 2007).

3 Results and Discussion

The programme has been used to obtain various results and a few representative ones are presented in this paper. Figure 5 shows the analytical results for different speeds of the wire. The experimental data for 2 m/min case is included in the graph for comparison. It can be seen that the faster the wire moves through the tube furnace, the longer it takes to reach the high temperature and thus shortening the soaking length. The differences between experimental and analytical results are not insignificant and may be due to simplifications made in the derivation of the method. For example, the assumption of radiation in a radial plane needs to be scrutinised more carefully. However, the overall qualitative comparison highlights that the method does provide data which is very difficult and expensive to obtain experimentally.

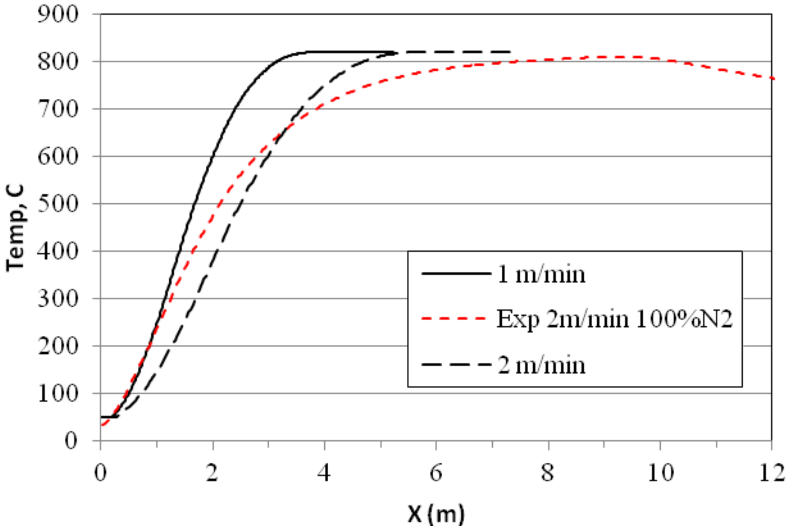

Figure 5: Prediction of heating rate for different speeds

A very important issue that needs highlighting is the influence of surface emissivity, ε which appears in Equation [4]. The ε values can be known for various conditions as found in many references such as Holman (2007). However, for small values of ε, the heat transfer is found to be very sensitive. We have plotted the temperature profiles for various combinations of the emissivity of tube wall and wire surface and only one representative curve is shown in Figure 6. The emissivity of the tube wall is kept at 0.8 because the best estimate is that it is not a smooth surface and is used over a long period of time. On the other hand, the stainless steel is fresh and has shiny surface as it enters the furnace. However, when it starts to glow inside the furnace its emissivity may vary significantly and no reliable data are available. Our results show that with higher emissivity, the results tend to come closer to the experimental value. From heat transfer considerations, the observations are correct because lower emissivity means higher thermal reflection and hence a slower heating rate.

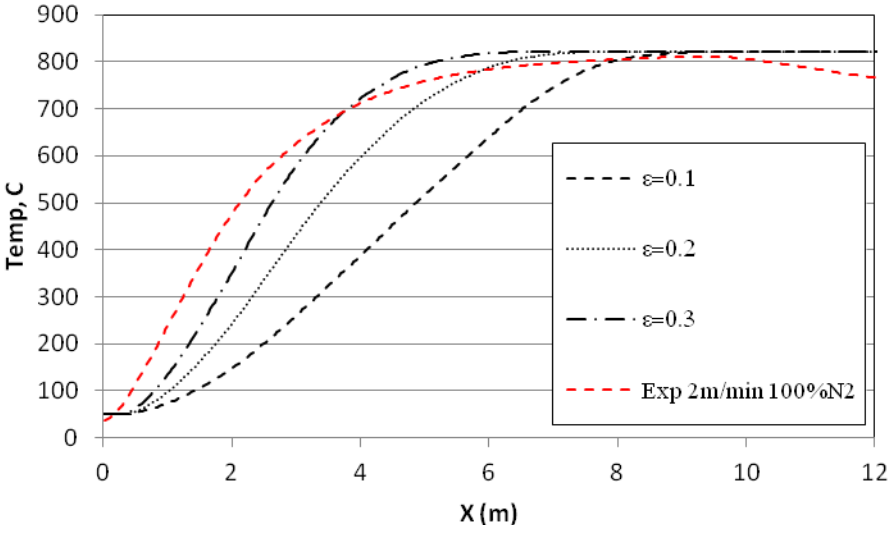

Figure 6: Prediction of heating rate for different emissivity values of wire surface

To analyse further, we have calculated the rate of heating of the wire (calculated for a temperature increase from 100 to 700 ^{o}C) and compared with experimental data. The graphs shows the interesting similarity between experimental and analytical data and also supports the observations made in the context of the uncertainty associated with emissivity values. These data are deemed to be important because the realignment of the crystals are known be dependent on the rate of heating. The data also highlight that the rates of heating are not linear and hence the gross 'heating rate' is a gross indication of the process.

Table 2: Rate of heating

Method	Speed/emissivity	Rate of heating ^{o}C/sec
Analytical	1 m/min	5.9
	2 m/min	7.1
Experimental	2 m/min	5.8
Analytical	$\varepsilon = 0.1$	4.2
	$\varepsilon = 0.2$	6.5
	$\varepsilon = 0.3$	6.7

4 CONCLUSIONS/FURTHER WORK

The methodology presented in this paper shows good promise to be used as a useful design tool for predicting temperature variations in tube furnaces. However, more work needs to be done to accommodate the following:

- Effect of reducing gas used around the wire.
- Extension of the method to include the cooling section.
- Collect more experimental data to validate the results from the current methodology

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