MODELING OF HEATING CYCLES FOR LARGE FORGINGS USING A PC-BASED PROGRAM

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ABSTRACT

Three thermal models for simulating the heating cycles used for large forgings were developed during a National Science Foundation (NSF) sponsored summer faculty internship at BethForge, Inc. The first model is for the heat treatment and quenching of forged rolls. The second model deals more directly with the forging operation itself and examines the temperature profile in an ingot during initial heating, forging and a subsequent reheat cycle. The third model examines a single heating cycle for a large axisymmetric ingot or forging. These models were an adaptation of a public domain finite element code. They were designed for easy operator input, rapid calculation on a personal computer and effective display of the temperature profiles. This paper shows some of the results that can be generated using these models with an emphasis on the types of information that can be obtained.

INTRODUCTION

This section will describe both the general philosophy used in the development of the computer models and the specific features that are addressed in each model. The next section of this paper will present a study that was performed with one the computer models to examine the effect of ingot size, heating rate and hold at 1300°F on the surface to center temperature difference during heating.

BethForge, a subsidiary of Bethlehem Steel, produces and heat treats large open die forgings for a variety of applications. These applications include forged rolls for rolling mills, large components for nuclear reactors, large rotors for electrical power generation and other large custom forgings. To produce these products, BethForge employees the melting and vacuum process capabilities necessary to produce high quality steel. Other capabilities include 10,000 ton and 2500 ton open die forging presses, along with the heat treatment and machining capabilities to produce products with a wide variety of characteristics.

At BethForge there are several heat treatment processes that could benefit from a reliable, user-friendly and rapid computer model. The aspects of reliability, user-friendliness and rapid response time are extremely important, especially in a production environment. Hence the computer models that were developed as part of the National Science Foundation (NSF) faculty industrial internship program, possess these characteristics.

The reliability of the model is paramount. The model needs to reflect the reality of the situation, no matter how friendly or how quickly it can produce results. If reliability is missing then the results are useless. In this work a finite element model (FEM) program that had been developed for heat flow analysis for the storage of nuclear waste was adapted to the present processes. The code called "Determination of Temperature" (DoT) which is in the public domain underwent a rigorous quality assurance certification [1,2]. The results of the present models were also verified both with finite difference calculations and with some limited experimental measurements. In these verifications studies, the computer models that are described in this paper were found to be quite reliable.

The aspect of "user friendliness" was handled in three ways. The first was to develop these models to run on a microcomputer. This allows the people directly involved with the heat treatment process to run these programs on a computer that they are comfortable with. A PC based program is also easily available to remote production facilities. The second aspect was the development of the input menus that are used in the models. These menus were of a screen input type and dealt only with the process specific information, such as ingot diameter, initial ingot temperature, furnace cycle, forging times, *etc.* The FEM specific information and furnace characteristics such as element size, iteration time, convective heat transfer coefficient, *etc.* are stored in a separate file which the operator does not normally need to access. The third aspect of user friendliness was the development of the output screens. The resulting thermal profiles are plotted directly on the computer screen as temperature versus time plots that are directly analogous to the strip chart recordings that are normally used in the industry. Digital values of the temperature are also displayed simultaneously. This type of display provides a convenient means to view the results in a familiar fashion. Figure 1 shows the input screen menus as well as a black and white version of the color display that is generated by these programs. This final display figure (see Figure 1c) shows four temperature profiles as well as the furnace temperature as a function of time.

To run one of the models the following type of computer system is needed: IBM 386 PC or compatible, VGA graphics, math coprocessor, hard disk with about 1 MB free, 640K of RAM and MSDOS 3.3 or higher

The three programs that were developed are the following:

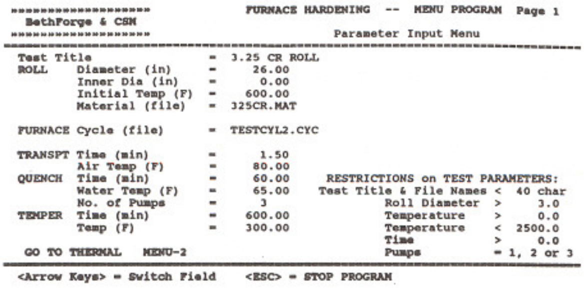
1. A program to model the furnace hardening of steel rolls. The furnace cycle, quench conditions and tempering conditions can be specified by the user. The program predicts the thermal profiles at various depth locations and calculates a depth of hardness for the specified process and material.

2. A program to model the thermal changes that occur in an ingot (or forging) during heating, forging and then reheating. The user can specify the heating conditions, forging conditions and reheating conditions. The program predicts the thermal profiles at various depth locations and calculates the instantaneous temperature gradient as well as the maximum temperature gradient in the piece during all three processes.

3. A program to model the heat treatment of ingots or forgings. The user specifies the furnace cycle and the program predicts the thermal profiles at various depth locations in the forging. The program also determines the instantaneous temperature gradient as well as the maximum temperature gradient in the forging during the heat treatment.

Each of the three programs is started by executing a control program. The user is presented with a series of menus where the processing conditions can be specified. The calculations are performed in a FEM program which simultaneously displays the temperature profiles as a function of time. This display is analogous to a strip chart recording of thermocouple measurements. A detailed output file is also generated during the calculations phase of the FEM program.

a)



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*******************                    FURNACE HARDENING  --  MENU PROGRAM  Page 1
 BethForge & CSM
*******************                              Parameter Input Menu
-------------------------------------------------------------------------------------
 Test Title                  =  3.25 CR ROLL
 ROLL    Diameter (in)       =    26.00
         Inner Dia (in)      =     0.00
         Initial Temp (F)    =   600.00
         Material (file)     =  325CR.MAT

 FURNACE Cycle (file)        =  TESTCYL2.CYC

 TRANSPT Time (min)          =     1.50
         Air Temp (F)        =    80.00
 QUENCH  Time (min)          =    60.00     RESTRICTIONS on TEST PARAMETERS:
         Water Temp (F)      =    65.00    Test Title & File Names <  40 char
         No. of Pumps        =    3                  Roll Diameter >     3.0
 TEMPER  Time (min)          =   600.00              Temperature   >     0.0
         Temp (F)            =   300.00              Temperature   <  2500.0
                                                     Time          >     0.0
  GO TO THERMAL   MENU-2                             Pumps         = 1, 2 or 3
-------------------------------------------------------------------------------------
 <Arrow Keys> = Switch Field    <ESC> = STOP PROGRAM
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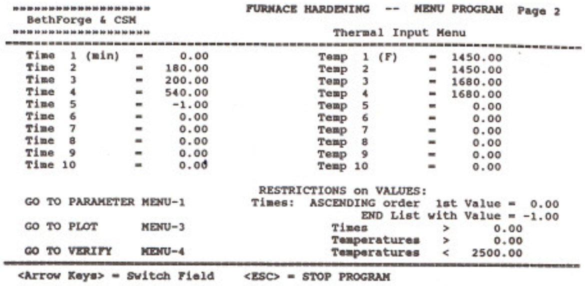
b)



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*******************                    FURNACE HARDENING  --  MENU PROGRAM  Page 2
  BethForge & CSM
*******************                              Thermal Input Menu
-------------------------------------------------------------------------------------
   Time  1 (min)  =     0.00               Temp  1 (F)     =  1450.00
   Time  2        =   180.00               Temp  2         =  1450.00
   Time  3        =   200.00               Temp  3         =  1680.00
   Time  4        =   540.00               Temp  4         =  1680.00
   Time  5        =    -1.00               Temp  5         =     0.00
   Time  6        =     0.00               Temp  6         =     0.00
   Time  7        =     0.00               Temp  7         =     0.00
   Time  8        =     0.00               Temp  8         =     0.00
   Time  9        =     0.00               Temp  9         =     0.00
   Time 10        =     0.00               Temp 10         =     0.00

                                       RESTRICTIONS on VALUES:
   GO TO PARAMETER MENU-1             Times:  ASCENDING order  1st Value =  0.00
                                                  END List with Value = -1.00
   GO TO PLOT       MENU-3                        Times             >      0.00
                                                  Temperatures      >      0.00
   GO TO VERIFY     MENU-4                        Temperatures      <   2500.00
-------------------------------------------------------------------------------------
  <Arrow Keys> = Switch Field    <ESC> = STOP PROGRAM
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c)

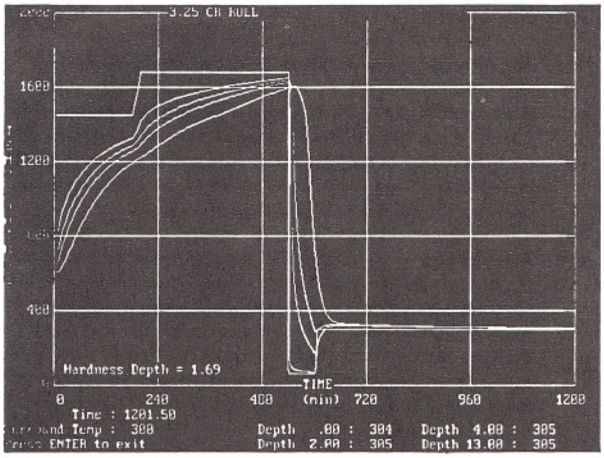

Figure 1: Examples of the computer input menus and the final display a) shows the initial input menu where the user specifies the geometry, quench and temperature conditions, b) shows the furnace cycle used during the heat treatment, and c) shows the temperature-time profiles for the furnace and at various depths in a forged roll during a heat treatment, quench and temper cycle.

Once the FEM program is complete the user can then rerun the menu program to make changes to the processing conditions and see what effects they have on the predicted thermal profiles.

Model 1: Heat Treating and Quenching of Forged Rolls

Forged work rolls for rolling mill applications are often vertically heat treated and quenched. The purpose of this treatment is to produce a strong, wear resistant martensitic structure on the surface of the rolls. From a user's perspective, it would be highly desirable if this hardened case on the surface could be increased to a larger depth in a consistent fashion. The key to increasing this hardened layer is a better understanding of the thermal heat treatment and subsequent quench and temper. The rate of cooling will affect the formation of martensite as well as the steel characteristics and thus the depth of the case.

A one-dimensional radial heat flow model was developed to simulate this heat treatment, quench and subsequent tempering process. This model allows the user to explore various heat treatment and quench cycles, without the need to run costly experiments. For example, the influence of various austenitizing temperatures and times on the thermal profile of the roll prior to quenching, which controls the ausentite formation of these roll steels and hence, the attainable hardness, can be investigated. In addition to modeling the effects of various austenitizing variables on the roll thermal gradient, the influence of the quench severity and quench time on the cooling rate can also be explored. Based on the cooling rate during the quench, a measure of the actual depth of hardness is predicted by the simulation. Although metallurgical structures are not directly predicted from the computer model, they can be inferred from a knowledge of the time-temperature-transformation behavior of the steel.

Model 2: Heating, Forging and Reheating

The goal of this model was to examine in detail the heating of ingots for open die forging and especially the reheating of partially forged ingots. Sometimes, during the forging process, the forging will have cooled to such an extent that continued deformation is no longer viable. At this point the partially forged ingot with its intermediate shape must be reheated. The critical question is: what is the minimum time that can be used to bring this large partially forged ingot back to a temperature sufficient for completion of the forging? The reheated ingots are often left in the furnace for extended periods to insure that they have reached sufficient temperature and to accommodate operator schedules. By modeling the thermal process of initial heating of the ingot, cooling during forging, and reheating when it is placed back into the furnace, the minimal time for the reheat can be determined. This can be helpful in saving energy and in proper scheduling of the final forging stage. A quick and reliable model was developed to determine this minimal reheat time.

Model 3: Heating of Large Axisymmetric Ingots or Forgings

The third model is a derivative of the second one. It focuses on the heating of large axisymmetric ingots or forgings. The questions that can be addressed by the use of this model concern the proper heating rates, the soak times and the minimization of temperature gradients through the ingot or forging during heating. A wide variety of furnace cycles could be used to achieve the appropriate temperature in the ingot or forging. This model allows for a critical and quantitative assessment of these cycles. Examples of how this model can be used, are describe in the next section of this paper.

All three programs run on a PC. They allow easy input of information by the user and provide a clear graphical display of the results. Overall these programs provide a viable tool for use by heaters and furnace operators in gaining a better insight into the thermal treatment cycles that are used for ingots, forgings and rolls.

RESULTS FROM THE HEATING PROGRAM

To show the usefulness of these programs a systematic study was performed to examine the temperature difference between the center of a steel ingot and its surface during the heating from the cold state of 100°F to the forging temperature of 2300°F. The variables that were considered were ingot diameter, heating rate, and whether or not there is a hold time at 1300°F during the heating cycle.

The steel that was used for these simulations is a medium carbon steel with the thermal conductivity as a function of temperature as given in Figure 2. Its heat capacity as a function of temperature is given in Figure 3. The ingot sizes that were considered are 24 inch, 42 inch and 60 inch diameters. The heating rates were 50°F/hr, 75°F/hr, 100°F/hr, 150°F/hr and 200°F/hr. If a hold at 1300°F was part of the cycle, it was 4 hr for the 24 inch ingot, 12 hr for the 42 inch ingot and 15 hr for the 60 inch ingot. It was also assumed that the furnace was initially at 300°F at the start of the heating cycle and that there was a final soaking time at 2300°F of 4 hr for the 24 inch ingot, 12 hr for the 42 inch ingot and 15 hr for the 60 inch ingot.

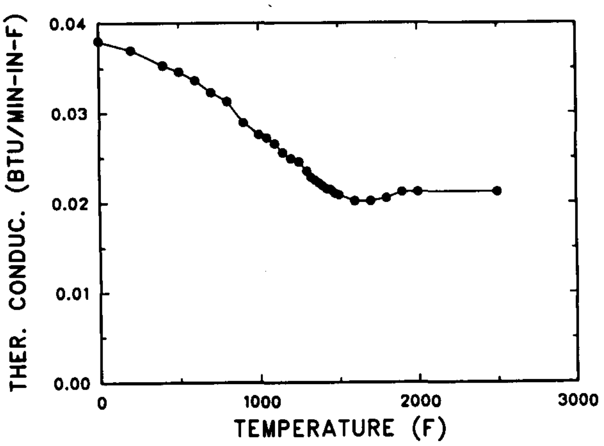

Figure 2: Thermal conductivity data for the medium carbon steel used in the example simulations.

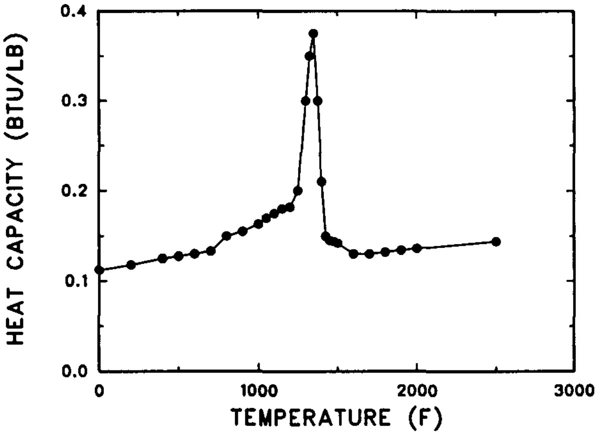

Figure 3: Heat capacity data for the medium carbon steel used in the example simulations.

The actual computer time to run each simulation on a 486/33 PC was between 30 seconds for the 200°F/hr heating of the 24 inch ingot and 4 minutes for the 50°F/hr with a hold for the 60 inch ingot. Temperature for the furnace, ingot surface and ingot center were calculated at each 5 minute time step during the prescribed heating cycle. Figures 4 and 5 show the temperature versus time profiles that are generated by the program and are equivalent to the results that are directly display on the computer screen at the end of each computer run.

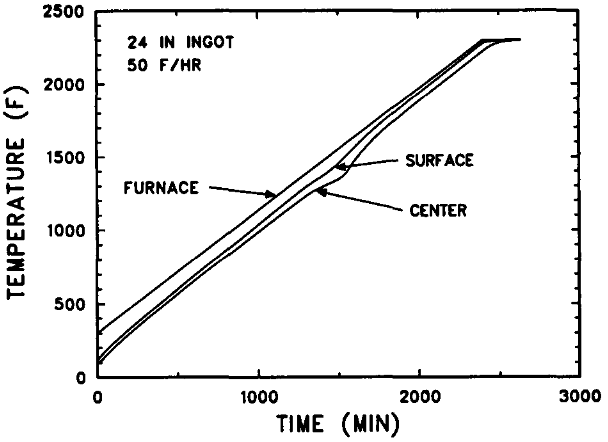

Figure 4: Temperature time profiles for the furnace, ingot surface and ingot center heated at 50°F/hr. The ingot size is 24 inch diameter.

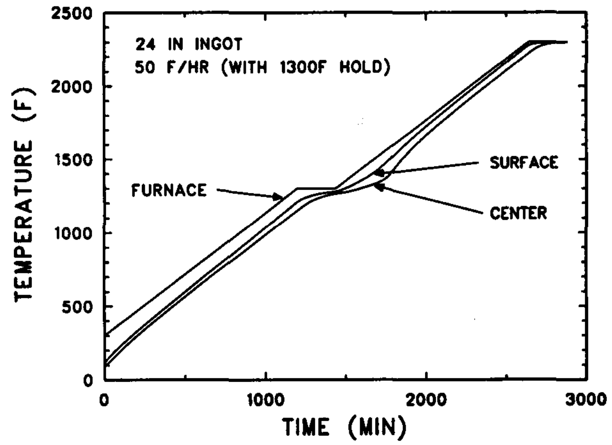

Figure 5: Temperature time profiles for the furnace, ingot surface and ingot center heated at 50°F/hr and held at 1300°F for 4 hour. The ingot size is 24 inch diameter.

Figure 4 is the heating cycle for the 24 inch ingot at 50°F/hr. It shows the furnace temperature as well as the surface and center temperatures of the ingot. The temperature difference that was explored in this study is the difference between the surface and the center temperatures. This temperature difference is calculate at each time step in the simulation. Figure 5 shows the equivalent heating cycle for the same size ingot as Figure 4 with the exception that a 4 hour hold time is incorporated into the cycle at a furnace temperature of 1300°F. This type of hold time is often used in industrial practice for ferrite steels to insure that the ingot does not have a large thermal gradient within it which may cause ingot cracking or thermal shatter.

Figure 6 shows the temperature difference between the surface and center of the ingot as a function of furnace temperature for the 24 inch ingot at various heating rates. The equivalent information, but as a function of ingot surface temperature, is given in Figure 7.

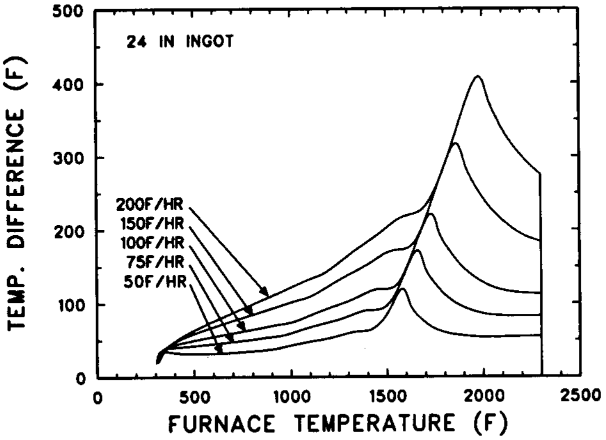

Figure 6: Surface to center temperature differences as a function of the furnace temperature for various heating rates. The ingot size is 24 inch diameter.

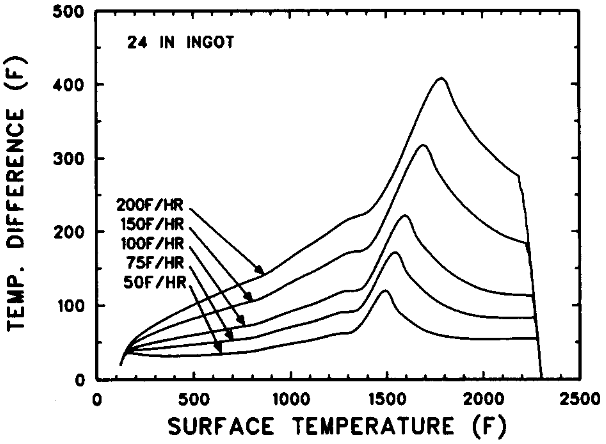

Figure 7: Surface to center temperature differences as a function of the surface temperature for various heating rates. The ingot size is 24 inch diameter.

As would be expected the higher heating rates caused higher temperature differences to occur within the ingot. The maximum temperature difference occurred when the surface of the ingot was between 1500°F (for the 50°F/hr heating rate) and 1750°F (for the 200°F/hr heating rate.) The maximum value for this temperature difference was between 119°F and 408°F.

Figure 8 shows the effect of a 4 hour hold at 1300°F on the temperature difference profiles for the 24 inch ingot at the various heating rates. As can be seen in comparing Figure 7 to Figure 8, the hold does decrease the temperature difference profiles. The maximum value for this temperature difference was between 107°F to 328°F which is a decrease of between 12°F and 80°F depending on the heating rate.

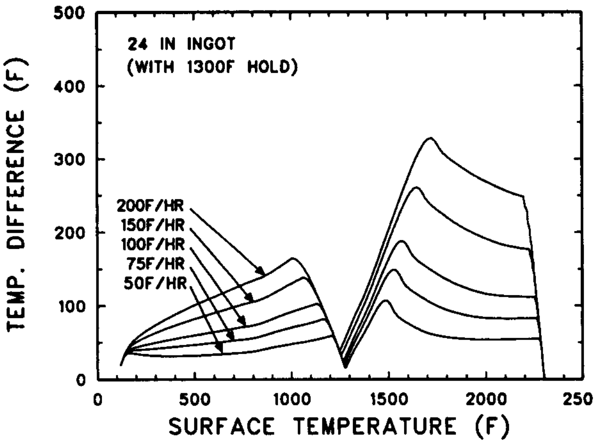

Figure 8: Surface to center temperature differences as a function of the surface temperature for various heating rates and with a 4 hour hold at 1300°F. The ingot size is 24 inch diameter.

Figures 9 and 10 show the temperature differences for the 42 inch ingot without a hold and with a 12 hour hold at 1300°F. Once again the maximum temperature difference occurs at the later portion of the cycle and is decreased with a hold at 1300°F. The other feature of note is that for the slowest three heating rates (50°F/hr,75°F/hr and 100°F/hr) the maximum temperature difference was seen during the heating cycle itself. For the two fastest heating rates (150°F/hr and 200°F/hr) the maximum temperature difference was obtained during the final soaking when the furnace was at 2300°F. The characteristics of the temperature difference curves indicate this variation. The slowest heating rate curves show a peak followed by a slowing decreasing slope then a rapid decrease in the temperature difference. Whereas the faster heating rate curves show a peak followed by a rapidly decreasing slope only.

Figures 11 and 12 show the temperature differences for the 60 inch ingot without a hold and with a 15 hour hold at 1300°F. This ingot size has the largest temperature differences of the three sizes investigated. Again the maximum temperature difference occurs at the later portion of the cycle and the hold at 1300°F decreases the maximum temperature difference. The faster four heating rates obtained their maximum temperature difference during the final soaking when the furnace was at 2300°F. The curve for the slowest heating rate (50°F/hr) has different characteristics and achieves its maximum temperature difference before the final soaking temperature is reached by the furnace.

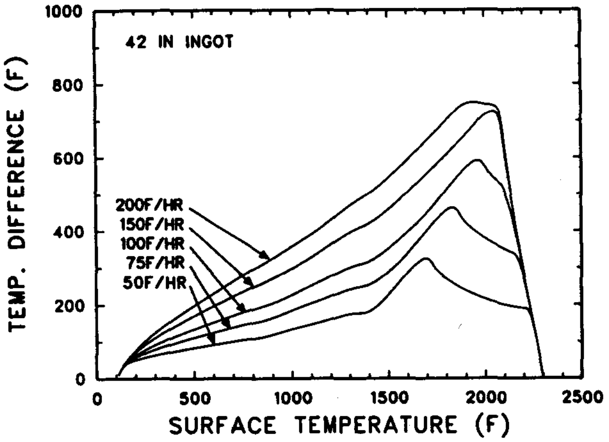

Figure 9: Surface to center temperature differences as a function of the surface temperature for various heating rates. The ingot size is 42 inch diameter.

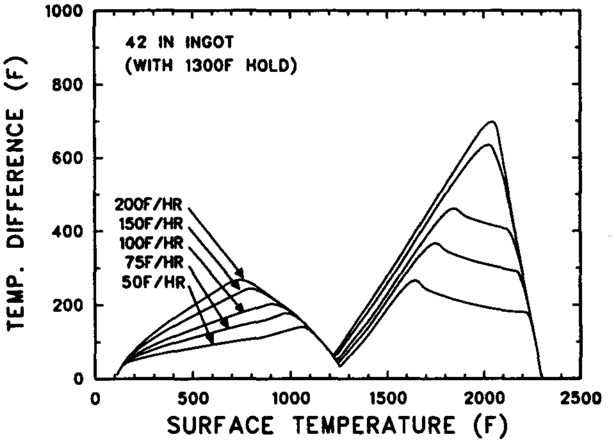

Figure 10: Surface to center temperature differences as a function of the surface temperature for various heating rates and with a 12 hour hold at 1300°F. The ingot size is 42 inch diameter.

Figure 13 is a summary graph for the effect of heating rate on the maximum temperature difference both without and with a 1300°F hold. Figure 13 shows hold each ingot size responds to each heating rate.

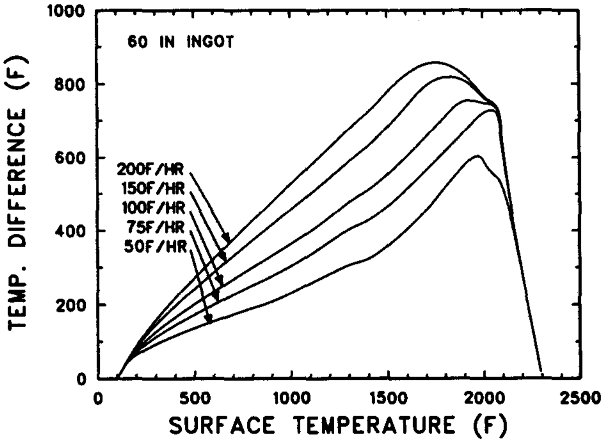

Figure 11: Surface to center temperature differences as a function of the surface temperature for various heating rates. The ingot size is 60 inch diameter.

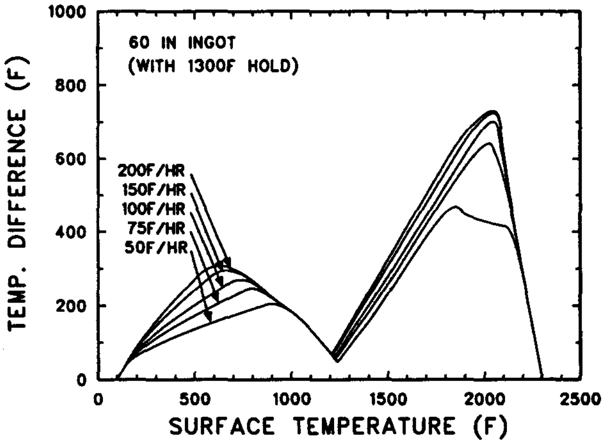

Figure 12: Surface to center temperature differences as a function of the surface temperature for various heating rates and with a 15 hour hold at 1300°F. The ingot size is 60 inch diameter.

DISCUSSION OF RESULTS

For this study that was conducted on the effect of heating rate and ingot size, there were 30 runs of the PC computer model. The time to run all 30 simulations was approximately 80 minutes. The heating cycles that were used for this study are not the only ones that can be simulated. The program allows for 127 different time-temperature points for each furnace heating cycle. This large number of points allows some very complex heating cycles to be analyzed.

The heating program, as illustrated in the above example, allows the operator to examine a large variety of heating cycles so that the "best" one can be used in the actual process. The "best" cycle is one that would minimize furnace time, minimize fuel consumption and also maintains reasonable values for the surface to center temperature difference.

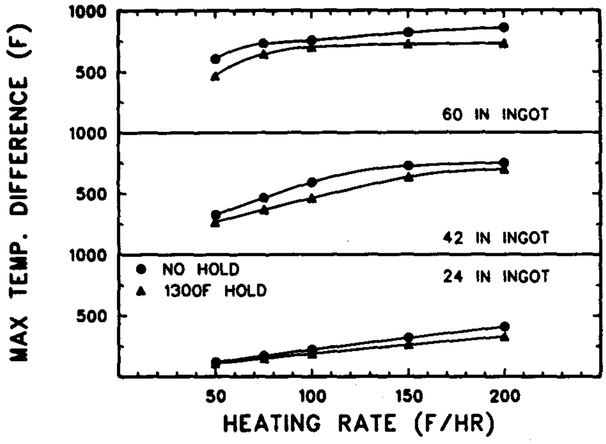

Figure 13: Maximum surface to center temperature difference as a function of heating rate, ingot size and whether or not a 1300°F hold was used during the heating cycle.

SUMMARY

Three thermal models for simulating the heating cycles used for large forgings were developed. They were designed for accuracy, user friendliness and rapid calculation on a personal computer. The results that are obtained from these models are the temperature profiles that occur within the ingot, forging or roll at various depths from the surface. The values for these temperature versus time curves can be used to examine several features about the heat treatment process. The example presented in this paper showed the effect of ingot size, heating rate and hold at 1300°F on the surface to center temperature difference that occurs in a medium carbon steel ingot.

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[2] "DOT - A Nonlinear Heat Transfer Code for Analysis of Two-Dimensional Planar and Axisymmetric Representations of Structures", ONWI/E512-02900/CD-16 420-05G-01A, 1982.