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A Model for Predicting the Response in Phase Transformation Powder Metallurgy Steel Components to Heat Treatment

[1]Natarajan and [2]P.K. Chawdhry

[1]Department of Mechanical Engineering, SaiNath University, Ranchi, Jharkhand, India
[2]Department of Mechanical Engineering,Galgotia Institute, Noida

Abstract: The aim of the heat treatment of steel fabricated components is to improve the characteristics of the metal components to meet the criteria pre-established quality assurance. However, the heat treatment process often creates considerable distortion, dimensional change and the residual stresses in the components. These thermal stresses are caused mainlyby generated by a nonuniform temperature distribution on the part and / or by transformation stresses due to the mismatch between the phase volume of the parent phase of products that can be formed by phase transformation. With the growing demand for tighter dimensional tolerances and better mechanical components from heat treated, properties is important for the manufacturer to be ableto predict the ability of a component that has been heat treated to a hardness and desired strength without suffering cracking, distortion and the change excessivedimensional. Several commercial softwares are available to accurately predict the response to heat treatment of forged steel components. However, these programs can not be used to predict the response to heat treatment of steel components which are made by powder metallurgy (PM) processes, because these components typically contain pores that affect, thermal and mechanical behavior of the material transformation.

Key words: Powder metallurgy · Powder materials · Copper powders · Green compacts

INTRODUCTION

Powder metallurgy (PM) components undergo considerable changes during heat treatment including changes in their mechanical properties, dimensions, magnitude and direction of residual stresses and metallurgical phasecomposition. Since the quality assurance criteria that a heat treatment of PM components must meet minimum requirements include mechanical properties and compliance with dimensional tolerances, it is necessary to heat treaters to be able to accurately predict these changes in order totake appropriate action to prevent its harmful effects and ensure the production of good qualityparts. Satisfactory heat treatment response is often measured by the ability of the component to be heat treated to a desired microstructure, hardness and strength level without cracking, distortion or excessive dimensional changes [1]. Besides reversible changes that are caused by thermal expansion and contraction, metal components undergo permanent dimensional changes during the heat treatment. These permanent changes can be broadly classified into two groups according to their origin. These groups are: Dimensional changes with mechanical sources, including dimensional changes caused by stresses developed by external forces, the dimensional changes arising from thermally induced stresses and dimensional changes that are caused by the relaxation of residual stresses. Dimensional changes to metallurgic sources including dimensional changes that are caused by recrystallisation, precipitation solution and alloying elements and phase transformations. Residual stresses often adversely affect the mechanical properties of the components of PM. they are caused by thermal gradients in the parts during quenching and depend on the cooling rates, section thickness and material strength. The reduced severity of the quenching results in a lower level of residual stress, but with a corresponding decrease in the strength of heat-treated materials [2]. Residual stresses can also arise fromphase transformations during heat treatment The result of volumetric changes inherently associated with the crystal structure of the parent and product phases during phase transformations

Corresponding Author: Natarajan, Department of Mechanical Engineering, SaiNath University, Ranchi, Jharkhand, India

in the material. Several software packages that are able to predict the response to heat treatment forged steels are commercially available. In this paper, based on finite element model and the database needed to predict the response of powder metallurgy steels to heat treatment are presented and discussed. The model is based on a modification of commercially available software DANTE coupled to the ABAQUS finite element analysis software. The model requires an extensive database, including temperature and kinetics phasetransformation porosity dependent and temperature-dependent properties and specific porosity of the mechanical, physical and thermal phases of steel. This data was it developed for FL-4605 PM steel and isused in the model to predict dimensional change, distortion, residual stress and the type and amount of metallurgical phases present in the typical microstructure of a PM component after the component is subjected to one specified heat treatment program. Finally, these characteristics for commercial production FL-4605 PM steel component compared totheir counterparts predicted by the model were measured. The subroutine phase transformation is based on variable frame aninternal state in which the volume fraction of metallurgical phases is tracked over time and changing temperature. in this subroutine, the formation of ferrite, pearlite, bainite and is assumed to follow the kinetic diffusive transformation [3]. The martensitic transformation is supposed to be athermal; however, kinetics equations, which are written in the formof equations speed havean explicit dependence on the cooling rate. Material data for the phase transformation kinetics subroutine derives heating and cooling dilatometric measurements on three samples with significantly different levels of porosity. The details of the mathematical model and procedures used to obtain the parameters of the model for the kinetics of phase transformation eachphase the three levels of porosity. Thermal boundary conditions, namely, heat transfer coefficients as a function of temperature for different porosity levels were obtained by quenching probes CHTE FL-4605 made from steel PM. The other necessary thermal properties of FL-4605 PM steel, such as its heat capacity and heat conductivity is obtained from the literature and have been implemented in the subroutines as functions of temperature and porosity. The effect of the porosity on the various mechanical and thermal properties of the material are taken into account in the model data sets which include mechanical and thermal properties and processing characteristics of the alloy phase in every level of porosity and interpolating the parameters at the

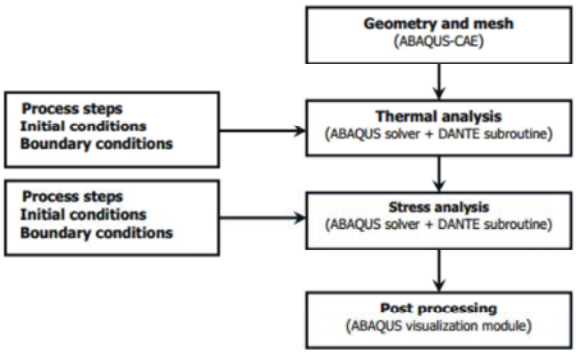

Fig. 1: Solution procedure for the combined model DANTE/ABAQUS

node level. A block diagram model of DANTE / ABAQUS combined displays. It consists of a geometry and mesh generators, post processor, thermal subroutine and the subroutine mechanics. Thermal subroutine is configured to solve the problem of heat transfer for each of the process steps of heat treatment, that is, the step of heating the furnace, the immersion quenching step tank and the step of cooling. The output file generated by thermal subroutine contains the thermal history of partduring the various process steps. The mechanical subroutine accesses the output file and calculates the residual stresses, displacements, the volume fraction of metallurgical phases and the hardness of the material for the entire temperature history of the piece [4].

Literature Survey: When steel alloys are cooled from the austenitizing temperature a solid state phase transformation occurs, resulting in a product phase that are larger in size and harder than the austenite phase parent. Thus during the decomposition of austenite matrix, because of the greater volume and strength of the product phase microscopic plastic flow occurring as the transformation procedure [5]. This phenomenon is known as transformation induced plasticity. Plastic deformation induced transformation must be included in the modeling of the final residual stresses during thermal cycling of a steel alloy, as omission of this parameter can not only lead to erroneous values of stress, but can also generate erroneous signals tensions residual predicted by the model. This article describes test matrices and measurement procedure for measurements of dilatometry to determine the transformation induced plasticity in FL-4605 alloy PMsteel. It is used under stress for plasticity dilatometry transformation induced by applying external static compression load just before the start of

the transformation. In this appendix, the detailed procedure for evaluating transformation plasticity caused by the austenite-martensite transformation and bainite transformation-austeniteto described. One of the challenges in modeling the thermal response of the material is the heat transfer coefficient. Even the most sophisticated software uses fundamental laws of heat flow to numerically model the heat transfer process [6]. As a result, the accuracy of model predictions is always dependent on the accuracy of the boundaryconditions, initial conditions and property data used in the equations of heat flow material. While materialproperty data is relatively easy to determine at the outset is generally known, the boundary conditions between the metal portion and the cooling medium, that is, the coefficient of heat transfer depends on many factors including the conditions initial, the geometryof part, chemistry portion and the cooling medium and the condition of the surface of the workpiece. Moreover, some of these factors can interact with one another. Becauseof the critical nature of the heat transfer coefficient in computer modeling, an effort was made to provide a system and method for accurately determining this parameter. The method involves a probe cooling heatedcylindrical machining from study material and equipped with a thermocouple connected to a system of rapid data acquisition in the cooling medium and the acquisition of the temperature-time profile. The dimensions of the probe are so chosensuch that the Biot number extinguishing process is <0.1. [7] This ensures that no significant thermal gradients are present in the radial direction in the probe. Therefore, a simple analysis of heat balance (usually referred to as a lumped parameter analysis) can be performed in the system (cooling medium probe +) to give the heat transfer coefficient. Since Bi <0.1, the error associated with the calculation of the heat transfer coefficient is less than 5%. [8] By contrast, an analysis of transfer of "reverse" heat can be performed on the data of temperature and time whereby the heat equation is solved numerically reverse (knowing the temperature-time profile and the heat equation, working backwards to get the heat transfer coefficient). The heat transfermethod can produce more accurate inverse values of heat transfer coefficient that the method lumped analysis. The intention of the specific phase depending on the temperature and the mechanical properties tests determine porosity elastic and plastic behavior of each phase in a range of temperatures and strain rates. This data is primarily used by the model of mechanics in DANTE to calculate the stresses developed in part to undergo heat treatment. These stresses are of two types, the stress due to the change in phase fraction and flow toplastic stresses arising because of thermal shock. The following tables indicate temperatures and strain rates for each test phase.

MATERIALS AND METHODS

Kinetic parameters of phase transformation were obtained by cooling dilatometry. dilatometry is based on the principle that during heating and cooling dimensional changes in the material due to both thermal expansion associated with temperature change and phase transformations. Sensitive, high-speed expansion meters are used to measure these changes as a function of time and temperature. The resultant data is then converted into discrete values of the strain to specific values of temperature and time during thermal cycling [9]. Strainas a function of time and temperature is then used to determine the start and completion of phase transformations. Two types of dilatometry measurements were performed on the samples. These are (1) measurement of isothermal transformation and (2) continuous cooling transformation measurements. The data of measurements of isothermal transformation parameters to provide the kinetic diffusive transformations, asthe austenite into bainite and austenite to ferrite transformation/perlite. Furthermore, the data measurements provide continuous cooling transformation kinetics parameters for transforming austenite to martensite transformation. Sectionsdetail follows procedures that were used to make these measurements. Each specimen was subjected to conditioning prior to the test run in order to remove the residual stress and stabilize the position of the test sample within the apparatus. This treatment involves heating the sample to 850°C±5°C at a nominal rate of 10°C/s, holding the sample at 850°C for 5 minutes and then cool to room temperature with cooling rate of 100°C/s [10]. The specimen was not removed from the appliance before performing dimensional measurements. This conditioning cycle is designed such that each specimen has the same starting microstructure (martensite in this case) before characterizing the behavior of transformation. The critical temperatures Ac_3 $Ac_1$and were determined from samples that are independent of those used for the measurement processing. The sample was heated to 600 ± 5°C at a nominal rate of 10°C/s. Heating was then continued at a nominal rate of 28°C/h while the strain was measured continuously until the Ac1 and Ac3temperatures were identified. Each isothermal transformation thermal cycle consisted of heating a sample to an austenitizing temperature of 850°C ± 5°C at a nominal rate of 10°C/s.

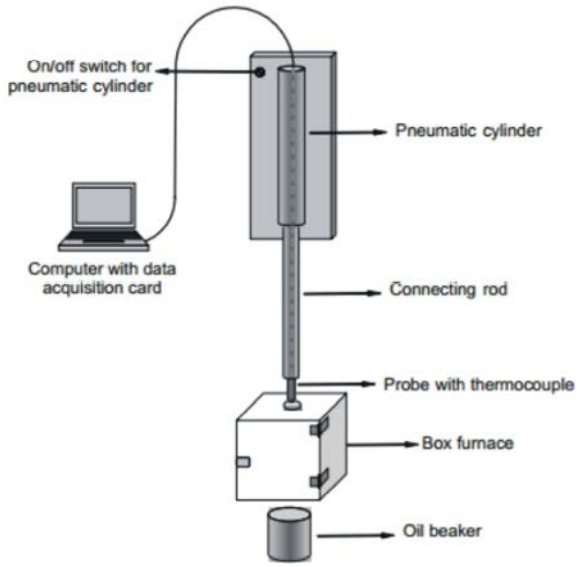

Fig. 2: Apparatus used to measure the heat transfer coefficient for the rapid cooling

The sample was held at this austenitization temperature for 5 minutes and then quenched to the temperature of isothermal holding. A cooling rate of at least 175°C/s was used. During cooling, the temperature of the sample not undershoot the isothermal keep the temperature over 20°C and stabilized at the isothermal holding temperature within 2 seconds. The sample temperature is maintained within ± 5°C isothermal hold temperature for dimension measurement. The sample was held at the isothermal hold temperature and its dimensions measured continuously until the transformation was 100% complete [11]. Then, the sample was rapidly cooled to room temperature. Data is sampled and recorded at a rate of at least 5 measurements per second dimension and a different specimen was used for each thermal cycle. Data collectedfrom these measurements for specimens with 100% density, because the austenite transformation were subjected to different temperatures bainite transformation [12].

Measurement of the Heat Transfer Coefficient: The method used to measure the heat transfer coefficient is to extinguish a heated cylindrical probe is machined from the test material in the middle of the temple and acquire temperature-time profile. The apparatus used for this purpose is shown in Figure 2 and consists of an electric box furnace for heating the probe, a connecting rod connecting the probe to a pneumatic cylinder which allows for automatic termination of the tube in a beaker containing the oil cooling and a computer system connected to a fast data acquisition. A k type thermocouple inserted into the geometric center of the probe continuously measures the temperature of the probe [8-10]. The dimensions of the probe are selected so that the number of the cooling process is Bi<0.1. This requirement ensures that significant temperature gradients are not present in the radial direction of the probe. Therefore, a simple analysis of heat balance (usually referred to as a lumpedparameter analysis) can be performed in the system (probe + cooling medium) to give heattransfer coefficient. Bi <0.1, the error associated with such calculations of the heat transfer coefficient is less than 5%.

$$h = -\frac{\rho V C_P}{A_s (T_s - T_f)} \frac{dT}{dt} \quad (1)$$

A balance of heat applied to the results of the probe in equation 1, which is used to calculate the heat transfer coefficient on the surface of the probe in equation (1), h is the heat transfer coefficient in the probe surface, ρ, V, C p, are density, volume, specific heat and the surface area of the steel tube, respectively. T_s is the temperature at the surface Ofthe transducer which, due to the geometry of the probe, is approximately equal to the temperature measured at the center of the probe and T_f is the bulk temperature of the cooling medium. The heat transfer coefficient obtained by this method for FL-4605 PM probes of pressed steel and sintered at different levels of porosity [13].

RESULTS

Each continuous cooling transformation thermal cycle consisted of heating a sample to an austenitizing temperature of 850±5°C at a nominal rate of 10°C/s. The sample was held at the austenitizing temperature for 5 minutes and then cooled to room temperature at different cooling rates. Data was sampled and recorded at a frequency of a measurement of the dimension per degree Celsius. Linear cooling rates were used to the maximum possible cooling. For cooling rates where the linear control was not possible, the rate at 700°C was reported along with the cooling time from 800°C to 500°C. A different specimen was used for each thermal cycle. Data collected during these measurements of samples with a density of 100%. The data generated from measurements of isothermal and continuous cooling was used to generate the kinetic parameters for the austenite to ferrite, austenite into pearlite, austenite to bainite and austenite to martensite transformation.

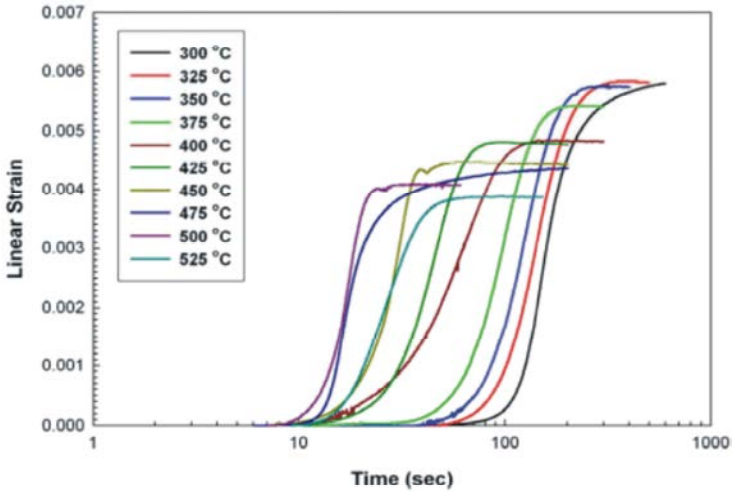

Fig. 3: Data processing time for isothermal bainite in different holding temperatures

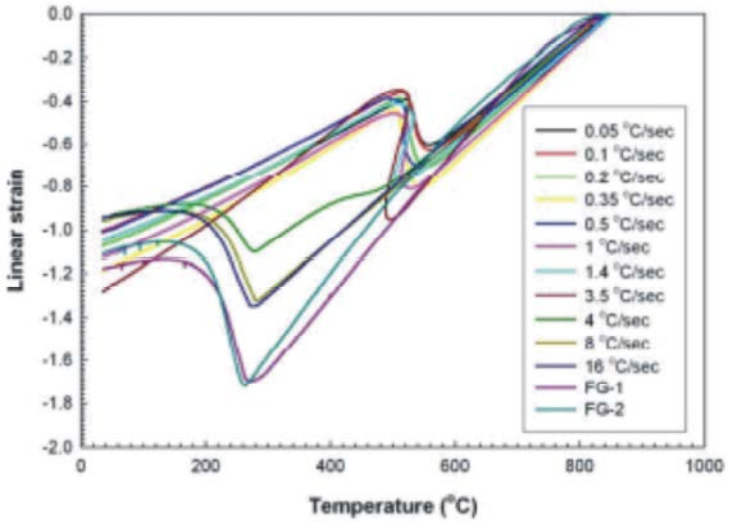

Fig. 4: Temperature data at different cooling rates during tests on continuous cooling transformation

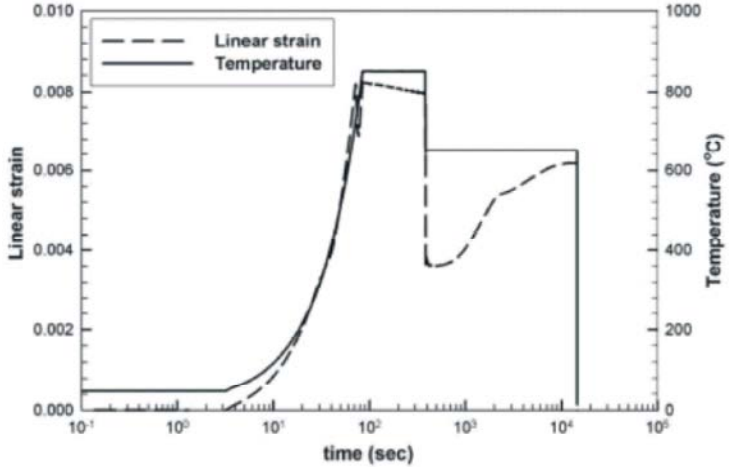

Fig. 5: Measured linear strain and temperature versus time for the austenite to ferrite transformation at 650°C in 95% dense sample steel

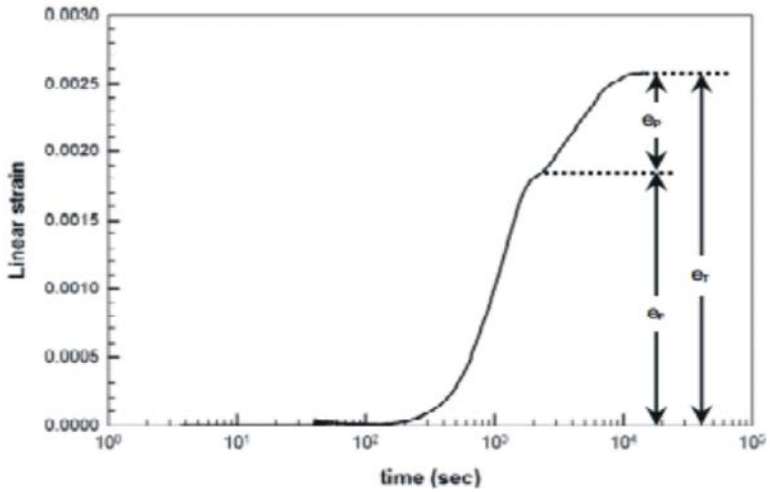

Fig. 6: Ime de transformación a partir de mediciones realizadas en isotérmicas 650°C en un 95% de muestras densas

Table 1: Design of experiments

Density levels	Isothermal holding temperature (°C)	Isothermal holding time (hrs)	Number of repetitions
3	600	18	3
3	650	4	3
3	675	24	3

The process shown in Figure is used to fit the data of the mathematical equations which were then tocreate used a database of transformation kinetics and a diagram Time-Temperature-Transformation (TTT) for the PM Steel. The TTT diagram for FL-4605 PM steel with two levels of porosity [14].

The heat treatment cycle consisted of the sintered parts in the heating oven at 850°C, maintenance at this temperature for 20 minutes and then quenching in oil with the upstanding portions and downward thinnest section. Twenty parts were heat treated in an inner quench batch furnace in an endothermic atmosphere with a carbon potential of 0.5 wt%. The effect of the porosity on the kinetics of the austenite to ferrite isothermal transformation in powder metallurgy steels are characterized by high speed cooling dilatometery. The measurements show that the presence of porosity in these steels reduces the stability of the austenite and hence shortens the incubation time of the processing. One type Avrami equation was fitted to the measured data in order to quantify the effect of porosity Avrami constants. in addition, samples with different porosity levels continuously goes after holding at 650°C for 900 seconds. Quantitative microscopic measurements performed on these samples showed an increase in the number and a decrease in the average diameter of ferrite grains with increasing porosity. Ishypothesized pores is in powder metallurgy steels increase the rate of nucleation of austenite ferrite providing high diffusivity paths carbon atoms that help accelerate its partition during transformation [15].

This is a plot of the linear measure the voltage and temperature versus time measure. The measured linear strain was normalized such that the zero voltage corresponds to the start of the hold after isothermal tempering the sample at 850°C and the processing time period was normalized such that zero corresponds to the start of cooling the sample to 850°C. Similar curves to the one shown were obtained for all conditions shown in Table 1. After cooling the dilatometer measurements, samples were cut from each specimen and mounted, polished and etched with 2%. microstructure after isothermal transformation at 600°C for 18 hours [17]. Similar micrographs were obtained for all the conditions shown in Table 1. Image analysis was performed on 10 micrographs representing each sample and the average volume fraction of the ferrite formed at each temperature and the density level is calculated. A test sample dilatometry curves that two events occur during processing measurement.These dilatometry are (1) the austenite to ferrite transformation and (2) the transformation of austenite to pearlite. Therefore, the volume fraction of ferrite formed during the processing was determined by dividing the stress caused by the formation of ferrite by total strain at the end of the measurement [18-22].

CONCLUSION

The based on finite element commercial code DANTE to predict the response of the floor steels to heat treatment was modified so that it can predict the response of PM steels to heat treatment by introducing porosity as a state variable model. An extensive database was developed for FL-4605 PM steel and contains information on the kinetics phase transformation, high temperature mechanical properties and heat transfer - all features as functions of temperature and the porosity for all phases that may be present in the steel, that is, austenite, ferrite / pearlite, bainite and martenisite. A byproduct of developing the database was created, for the first time, a time - temperature - Porosity - Transformation (PTSD) Diagram for PM steel. These diagrams are necessary for understanding and representing the effect of porositythat PMsteels invariably there on the kinetics of phase transformations in these steels. The response of a typical 4605-FL PMsteel part to heat treatment was simulated using the model and the model predictions were compared with measurements made in the similar parts that are commercially produced and commercially heat treatment. The predicted by the model dimensional changes, residual stresses and the amount of retainedaustenite after heat treatment were found to be in very good agreement with their measured counterparts. The practice is based on the principle that during heating and cooling of the steels, dimensional changes occur as a result of thermal expansion associated with the temperature change and the phase transformation. Dilatometer sensitive high-speed computer is used to detect and measure the changes in dimension that are produced as a function of time and temperature for a defined thermal cycle. This information is then converted to discrete voltage values for specific values of temperature and time during thermal cycling. Strain as a function of time or temperature (or both) can then be used to determine the beginning and end of phase transformations.

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