A Methodology for Evaluating Sinter-Hardening Capability

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Abstract:

The cost advantages of eliminating secondary heat treat operations by using sinter-hardening powders have become evident. The growth of high hardenability powders for ferrous powder metal components necessitates some methodology for determining the appropriate furnace cooling rate and powder alloy that will accommodate sufficient hardening of different sized parts. Fundamental data that characterizes the cooling rates in a specific furnace and fundamental data that describes the hardenability of the powder at air hardening cooling rates is required. Once available, finite element or finite difference methods can be used to model hardness profiles on a specific part. In this way, crucial parameters such as maximum allowable section size for sinter hardening on a given furnace can be determined.

Introduction:

Cost advantages of using ferrous metal powders that transform to martensite during the cooling stage of sintering are driving increased production of these powder grades. The cost advantage stems from the elimination of secondary heat treat operations. With the growth in use of these powders, it is imperative that powder metal component producers be able to understand how highly alloyed their powder needs to be and how much cooling power their sintering furnace must have to produce different section sized parts. Given the current state of available information, this is difficult at best.

It is accepted knowledge in the industry that some form of forced convective cooling in the sintering furnace is required to obtain a high degree of martensitic transformation. Conventional radiator fan cooling will not effectively harden the most common sinter-harden grades. Most industry work describes cooling rates in these furnaces on company specific fixtures or on thermocouples that are not imbedded in powder metal components. Furthermore, the cooling rates given do not always cover the relevant temperature ranges for all transformation products. For the bainite prone sinter-hardening grades, good cooling rates must be maintained in the

350-550° C (660-1020° F) range. One method for describing the cooling rate in this range for a given furnace is given by Duchesne, et al.[1] This is an excellent method to save on thermocoupling real parts and still describe the cooling rate. It does not, however, fundamentally describe the cooling provided by the furnace and therefore can not provide hardness and microstructure information for all sections of a part. Work by Davala, et al on FLC4608 is also very useful for determining critical cooling rates needed for that specific powder.[2]

On the metal powder side of things, all we seem to currently know is that we need a lot of Ni, Mo, and Mn. There is extremely limited information coming from powder producers. It is useful to use the standard Jominy end-quench test as a starting point for characterizing the hardenability of ferrous powders.[3,4] The most fundamental data provided on end-quenching of ferrous metal powders is the depth to Rockwell A 65 on an end-quenched Jominy bar compacted from the powder of interest.[5] This is useful in comparing powders but does not immediately indicate what cooling rate is required to get full martensitic transformation. Ideally, metal powder grades would have time-temperature-transformation (TTT) diagrams along with complete Jominy curves that describe not only the Rockwell A hardness but also microstructure and particle hardness (100g Knoop).

Proposed Method:

A fundamental method of describing the cooling in a sintering furnace is to determine the convective heat transfer coefficient at the surface of a component experiencing cooling within that specific furnace. This can be done with a well-known geometry specimen and with a minimum of two thermocouples. In the method described in this paper, a cube of FC0208 and of 6.85 g/cc density was used. One thermocouple was placed near the specimen but open to the furnace atmosphere and one was imbedded within the specimen at its center. Using conductivity (k), density (□□, and specific heat (C_p) information as a function of temperature (T), the heat transfer coefficient at the surface can be calculated using finite element methods (FEM) or control volume finite difference methods.[6,7] Essentially, the FEM modeling describes the amount of heat loss that must occur to provide for a temperature gradient between the outside thermocouple and the imbedded thermocouple for all times during the cooling. In most quenching problems, the heat transfer coefficient is described as a function of temperature because of the changes of phase in a liquid media that cools a component. In gas or air quenching, there is no change in phase so the heat transfer coefficient can be constrained to be constant with temperature.

Figure 1 shows cooling curves of the outside thermocouple open to the furnace atmosphere and the thermocouple imbedded at the center of the described 1"x1"x1" block. It also shows a model prediction of the temperature at the center of the block. Excellent agreement between the model and the measured result is shown. The surface heat transfer coefficient (h_c) was found to be 164.63 W/m^2/Deg C (29 Btu/ft^2/hr /Deg F). This h_c effectively characterizes the furnace cooling condition. The h_c for that furnace cooling condition can now be applied to any part. Furthermore, by using FEM the cooling rate at any point within a specific part can be known, provided that good information on conductivity, and specific heat as a function of temperature are known. A lower cooling condition on the same furnace was found to have h_c= 147.60 W/m^2/Deg C (26 Btu/ft^2/hr/Deg F).

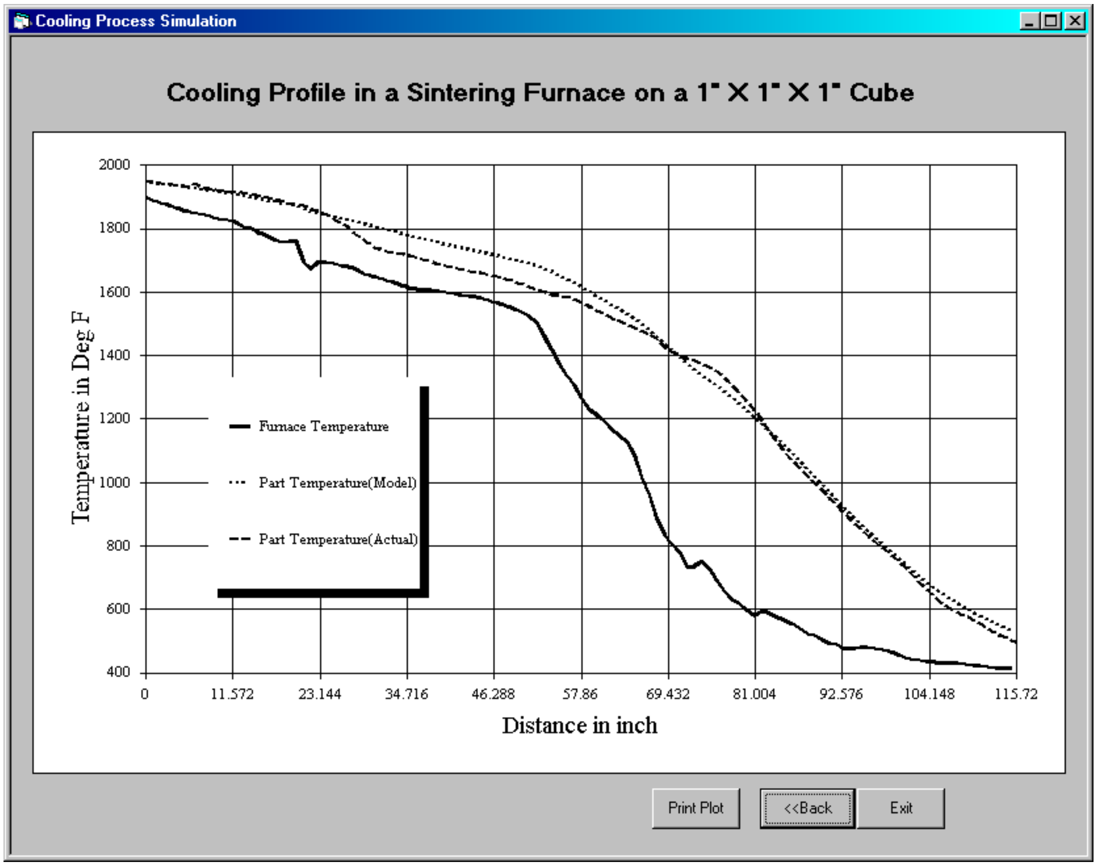

Figure 1 Cooling profiles (Temperature vs. distance) in a sintering furnace on a 1"x1"x1" cube. Bold line indicates temperature in the furnace near the cube, dashed line is the temperature measured at the center of the cube, and dotted line is the model prediction of the temperature at the center of the cube.

Information on the material's hardenability is also needed in order to fully predict the hardness and microstructure within a given component. The best current source for this is the end-quench Jominy test. The test provides standardized cooling but this cooling is not yet well described for powder metal materials. For wrought steels, the cooling rate at each Jominy position (1/16 inch intervals) at 1300° F is published.[8,3] The method for calculating the cooling rate can be reproduced for any powder metal grade using that grade's conductivity and specific heat but problems remain. At what temperature should the cooling rate be taken? This is not a big problem since the solutions to the heat transfer problem are described in terms of temperature and distance from the end-quench.

A bigger issue is that the standard end-quench Jominy test uses water as the quenchant. The cooling rates of interest for sinter-hardening are not encountered until at least Jominy position 20 and many times must go beyond Jominy position 40 to get non-martensitic structures. Figure 2 shows the Jominy curve for FLC4608.[9] Whether or not the standard Jominy bar can provide the resolution in hardenability needed to effectively model sinter hardening is still in question. It would be best to form a new end-quench test with a gas quenchant. Perhaps nitrogen flowing at a prescribed rate would provide a good standard test. As long as the heat transfer problem for the standardized test can be solved in terms of temperature and distance from the quenched end, any convenient and reproducible standard would be acceptable.

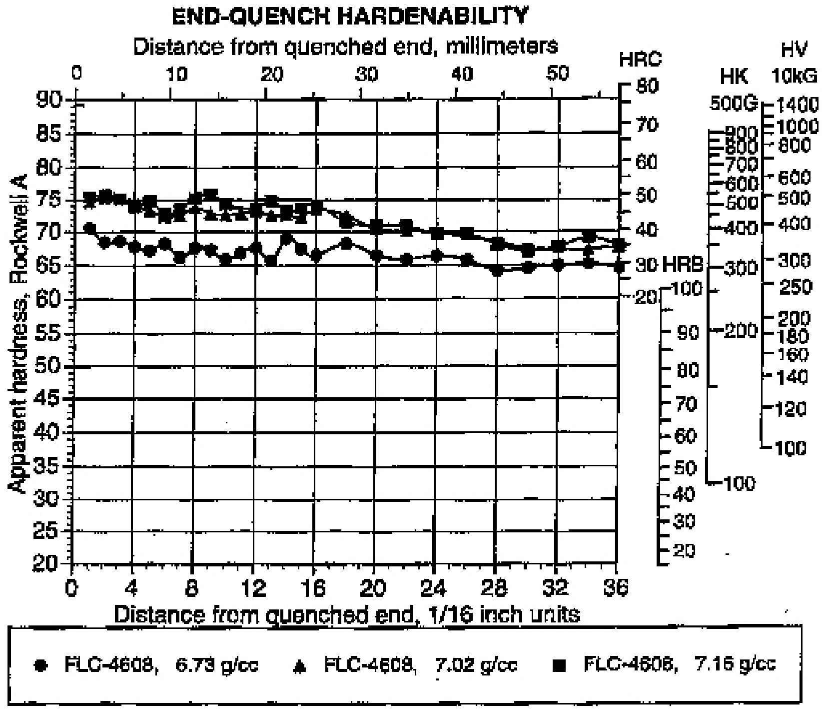

Figure 2 Jominy End-Quench results on FLC4608.[9] There is no significant drop in hardness through Jominy position 36.

The other problem to be addressed with the current Jominy method and with any new end-quench method is that of hardness testing. The fact that apparent hardness takes porosity and microstructure into account complicates the correlation from a standardized test to results on a real part. Particle hardness (Vickers or Knoop) may be a better indicator of true microstucture because porosity does not influence it. The problem is that the method is inherently less precise than apparent hardness and the indentation does not cover enough area to adequately average the microstructure. Unfortunately, Jominy testing in ferrous p/m will probably need to incorporate microstructure reading and area percentages of transformation products in order for the results to be fully transferable to modeling particular components in sinter-hardening.

Conclusions:

Successful modeling of hardness and microstructure on a particular ferrous powder metal component can be achieved with the following information:
1) Knowledge of the powder grade's conductivity and specific heat as a function of temperature.
2) Knowledge of the component's density.
3) Knowledge of the powder grade's hardenability at low cooling rates.
4) Knowledge of the convective heat transfer coefficient that characterizes the specific furnace cooling taking place when the component is run.

Methods for determining the information listed were presented. The benefits of modeling the sinter-hardening of a particular component are:

1) Knowing what section size can be effectively sinter hardened under each furnace cooling condition.
2) Optimizing furnace and powder grade selections. High cooling rates and high alloy systems may be overkill for many small section parts.

Recommendations:

1) Powder metal component producers should use methods by Duchesne, et al and the 0.5 deg. C/ s guideline minimum cooling rate as a first pass evaluation of a given furnace cooling condition.
2) A two thermocouple system with one thermocouple open to the furnace atmosphere and one imbedded at the center of an easily modeled geometry should be used to characterize the true cooling effectiveness of a set furnace cooling condition. This two thermocouple method will work with good FEM modeling.
3) A new end-quench standardized test should be instituted in the industry to define high hardenability powder grades.
4) Current standard Jominy testing and any new end-quench test should include plots of apparent hardness, microstructure, and particle hardness versus distance from the quenched end in the transition regions (90% martensite to 10% martensite).

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