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THERMAL ANALYSIS OF BUSHMASTER BARREL USING MAGNETIC REMANENCE

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13. ABSTRACT *(Maximum 200 words)*
Recent experiments on the role of phase transformations on magnetization revealed a strong response of the magnetic remanence to small, subtle transformation effects during thermal cycling. The results suggest that magnetic remanence can serve as a unique thermal analysis method for steels. One of the potential applications is to determine the thermal history of components. The present report describes the results of magnetic remanence thermal analysis on a specimen from the muzzle end of a Bushmaster barrel which, according to video recording of test firing, experienced excessive heating during testing.

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INTRODUCTION

In the past several years, we have developed simultaneous differential thermal analysis (DTA) and thermomagnetic analysis (TMA) methods to study details of phase transformations in steels. In the course of these studies, it was found that magnetic remanence is highly sensitive to small changes in quantity and type of magnetic material in a specimen. (Magnetic remanence is the magnetic induction remaining in a sample after the external magnetic field is turned off.) For example, the decomposition of approximately 5 percent retained austenite on heating a steel specimen can reduce the remanence by 50 percent or more. Large remanence changes are also observed on annealing. Similar large changes in remanence are observed during magnetic transformations at the Curie temperature of carbides in steels (ref 1). Since quantities such as the amount of retained austenite and type of carbide in steel are determined by prior thermal history, these observations indicate that thermal analysis using magnetic remanence can provide a new source of information on prior thermal history of components.

The purpose of the present study is to determine the thermal history of the muzzle end of Bushmaster barrel serial number (SN) 12373. This study is also a demonstration of the potential of magnetic remanence thermal analysis. A widely circulated videotape of the firing test of this barrel showed that the muzzle end behind the muzzle brake was heated to such an extent that it glowed brightly. The barrel was not instrumented to record temperature, and since there is an interest in developing accurate computation methods for temperature distributions in these barrels, an experimental method to determine thermal history can provide useful information for this effort.

In this study, the change in remanence on heating a specimen cut from the muzzle end of the Bushmaster barrel is compared with remanence changes in the same specimen after a variety of trial thermal processes were applied. The actual thermal history of the specimen is determined from the best match between the as-received and trial results. Successful selection of the actual thermal history by this method is indicated by the agreement with computer model calculations of the temperature cycle of the Bushmaster barrel in the test firing schedule.

THEORY

The following provides a simple model that describes the effect of transformations on remanence. For ferromagnetic materials, the fundamental quantities (in emu units) are the magnetic field H (oersteds), magnetic induction B (gauss), and magnetization M (gauss). These quantities are related through the equation

$$B = H + 4\pi M \tag{1}$$

The Faraday method is used to measure the magnetization M, which is determined from the force on the specimen given by

$$f = MV\partial H/\partial z \tag{2}$$

where f is the apparent change in sample weight, dH/dz is the field gradient, and V is the sample volume. An important feature of samples in rod configuration is the existence of free poles at the surface that reduce the field within the specimen. Expressed in terms of a demagnetization factor D, H is reduced in magnitude from the externally applied field H_E, according to the relation

$$H = H_E - D4\pi M \tag{3}$$

The magnitude of D depends sensitively on specimen geometry and field orientation.

We are concerned with magnetic remanence methods for monitoring transformations. The term "transformations" should be interpreted to include any metallurgical change that affects remanence. According to our investigations in steels, this includes a wide variety of processes such as actual changes of crystalline phase, Curie transitions in carbides, and tempering.

The high sensitivity of remanence to small changes in the volume of transformed material can be understood in terms of the parameters in Eq. (3). When a sufficiently high external field H_E is applied to a ferromagnetic specimen, a remanent magnetization M_R remains within the specimen after H_E is removed. According to Eq. (3), the internal field H produced by the free poles at the specimen surface is given as

$$H = -D4\pi M_R \tag{4}$$

This is an unstable configuration since the internal H-field exerts forces on the magnetic domains within the specimen that tend to reduce the magnetization M_R. The analog is a sandpile where the gravitational field exerts forces on the grains that tend to reduce the height of the sandpile.

The sandpile is the paradigm of self-organized critical systems, and we have demonstrated that magnetic transformations in ferromagnetic alloys are generally well-described in terms of self-organized criticality (ref 2). For sandpiles, the critical state occurs when the sandpile is at or near its maximum height and the sandpile surface is inclined at its angle of repose. For lesser heights, the sandpile is in a subcritical state. For magnetic systems, the corresponding critical state occurs at maximum specimen remanence. (For specimens with no surface poles (e.g., toroids), the maximum remanence is defined as the retentivity.)

A simple description of these phenomena can be obtained by assuming that the change in residual magnetization dM_R is proportional to the demagnetization field and the volume dv transformed from one magnetic state to another. Thus, we have

$$4\pi dM_R = cHdv \tag{5}$$

where we assume c to be a constant that depends only on such parameters as prior thermal history and alloy chemistry. Using Eq. (4)

$$dM_R = -cDM_R dv \tag{6}$$

and thus,

$$M_R = M_{RO}\exp(-cDv) \tag{7}$$

where M_{RO} is the specimen magnetization prior to the start of the transformation. Thus, the rate of change of remanence with volume transformed will be maximum for $v \sim 0$, and the remanence provides a sensitive measure of processes involving small volume changes in ferromagnetic specimens.

EXPERIMENTAL PROCEDURE

The TMA was performed using a modified Mettler TA1 Thermal Analyzer, which provides simultaneous digital recordings of DTA output and sample weight. Platinum sample holders of 9-mm diameter were used for sample and reference.

Two sets of Helmholtz coils were positioned around the furnace in a coaxial arrangement to produce a uniform and a gradient field *H*-field, which exert a force on a ferromagnetic specimen that is registered as an apparent change in sample weight. Specimen magnetization is calculated from Eq. (2). The system provides uniform fields of up to 200 oersteds and gradient fields of up to 2.0 oersteds/cm. TMA may be conducted with both the uniform and gradient *H*-fields applied during the programmed thermal cycle. The focus of the present study is the change in remanence during thermal cycling, and this is accomplished by applying only the gradient *H*-field after an initial magnetization with the uniform *H*-field.

Specimens for metallography, hardness, and remanence magnetization measurements were cut from the muzzle end of Bushmaster barrel SN 12373. The steel used in this barrel is D6AC. Since the procedure for the magnetic thermal analysis requires heating to 850°C for austenitization, the specimen was protected against decarburization by copper plating the steel and performing the thermal cycling in a helium-10 percent H_2 gas mixture. The specimen dimensions for the magnetic remanence tests were 1 mm by 4 mm by 20 mm. The specimen used for metallography and hardness measurements was taken from a region adjacent to the magnetic specimen.

RESULTS

Figure 1a shows the change in remanence on heating for the as-received specimen cut from the muzzle end of the Bushmaster barrel. Remanence units are tesla (1 tesla = 10^4 gauss). A dramatic reduction in remanence (approximately 80 percent) is observed on heating to 400°C.

Figure 1b is a plot of the derivative of the remanence versus temperature curve of Figure 1a. The derivative plot is preferred because it provides a clearer illustration of differences for the various heat treat processes.

Figure 2 represents the three trial cooling paths (from austenitization temperature to room temperature) used in the Mettler Thermal Analyzer.

Figure 3a shows a large difference between the results for the as-received specimen and for the same specimen subjected to the standard heat treatment: austenitized at 850°C, cooled along path B (intermediate rate) in Figure 2, and tempered at 600°C.

Figure 3b compares the results for the as-received specimen and for the same specimen austenitized at 850°C and cooled along cooling path A (slow rate) in Figure 2 (no temper). There is a large difference in the location of the two peaks.

Figure 3c compares the results for the as-received specimen and for the same specimen austenitized at 850°C and cooled along cooling path B (intermediate rate) in Figure 2 (no temper). This thermal history gives the best agreement between the two curves in the vicinity of the peak.

Figure 3d compares the results for the as-received specimen and for the same specimen austenitized at 850°C and cooled along cooling path C (fast rate) in Figure 2 (no temper). There is a substantial difference in the depths of the two peaks.

Figure 4 compares the results for the as-received specimen and for the same specimen austenitized at 950°C and cooled approximately along cooling path *B* (intermediate rate) in Figure 2 (no temper). As with Figure 3b, there is a substantial difference in the position of the two peaks.

Figure 5 shows the calculated cooling path for the muzzle end of a Bushmaster barrel after the standard test firing schedule. The heat transfer coefficients were calculated from the XKTCNOVA code developed by U.S. Army Research Laboratory (Aberdeen Proving Ground, MD) and the temperature distribution was computed by finite differences. A 19 percent scaling of the temperature distribution was used as a correction to raise the muzzle temperature to the 850°C temperature indicated by the present measurements at the end of the firing schedule. Comparison with the cooling curves in Figure 2 shows approximate agreement with curve *B* (intermediate cooling rate), which is the trial cooling path that gives the best agreement between the remanence curves of the as-received and laboratory thermal processed results (Figure 3c).

Figure 6 is a photomicrograph (500X) of the specimen cut from an area immediately adjacent to the specimen used in the magnetic tests. The microstructure appears to be predominantly untempered martensite with some bainite. The hardness of 57 on the Rockwell C scale is consistent with an intermediate cooling rate and essentially untempered microstructure. According to the *Aerospace Structural Metals Handbook* (ref 3), the maximum hardness of D6AC steel is approximately 62 on the Rockwell C scale.

DISCUSSION

The rapid reduction in remanence on heating in Figure 1 arises from the combined effect of the Curie transformation in carbides and the transformation of retained austenite to bainite. The Curie transformation temperature of cementite is 210°C. The Curie temperature will vary, however, as cementite is alloyed with other constituents such as chromium and vanadium. The details of carbide alloying depend upon prior thermal processing.

The transformation of retained austenite to bainite is the predominant cause of the large reduction in remanence in the present measurements. This transformation occurs in the 200 to 350°C range. As with carbides, the amount and carbon content of retained austenite also depends on thermal processing. Consequently, the remanence response of heating is expected to be sensitive to thermal history, as observed.

As Figures 3 and 4 indicate, the muzzle of Bushmaster barrel SN 12373 was heated to 850°C after the 150 round test and subsequently cooled to ambient temperature at an intermediate cooling rate (i.e., cooled to 100°C in ~40 minutes). The microstructure, hardness, and calculated cooling path are all consistent with the thermal history determined by magnetic remanence thermal analysis.

The present information is also significant for designers and analysts concerned with refining methods for computing temperature distributions in barrels during firing. Specifically, the data indicate that the model prediction of the temperature of the muzzle at the end of the 150 round firing schedule was approximately 19 percent too low to account for the observed remanence results.

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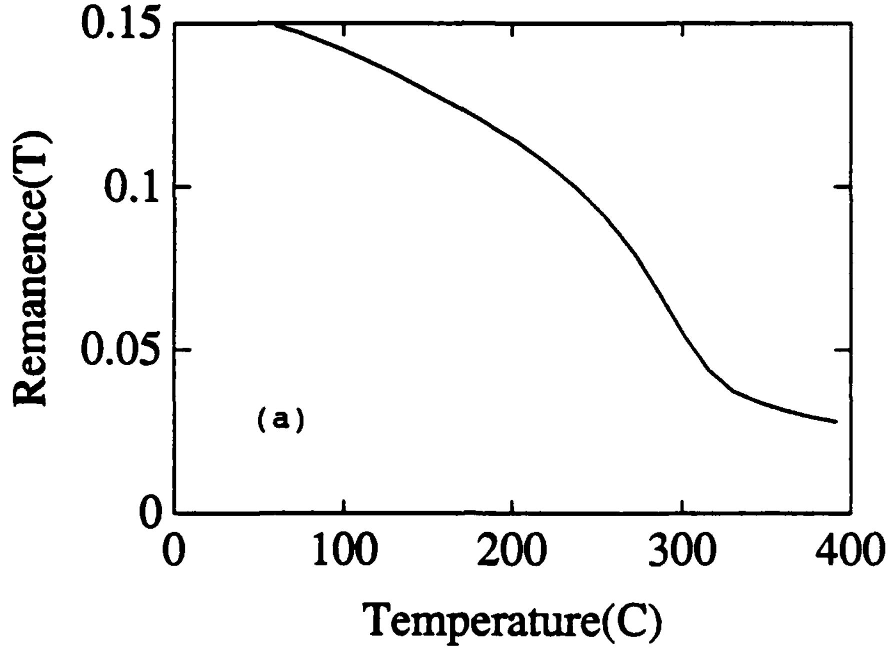


Figure 1a. Reduction in remanence (in tesla) on heating the as-received Bushmaster muzzle specimen to 400°C.

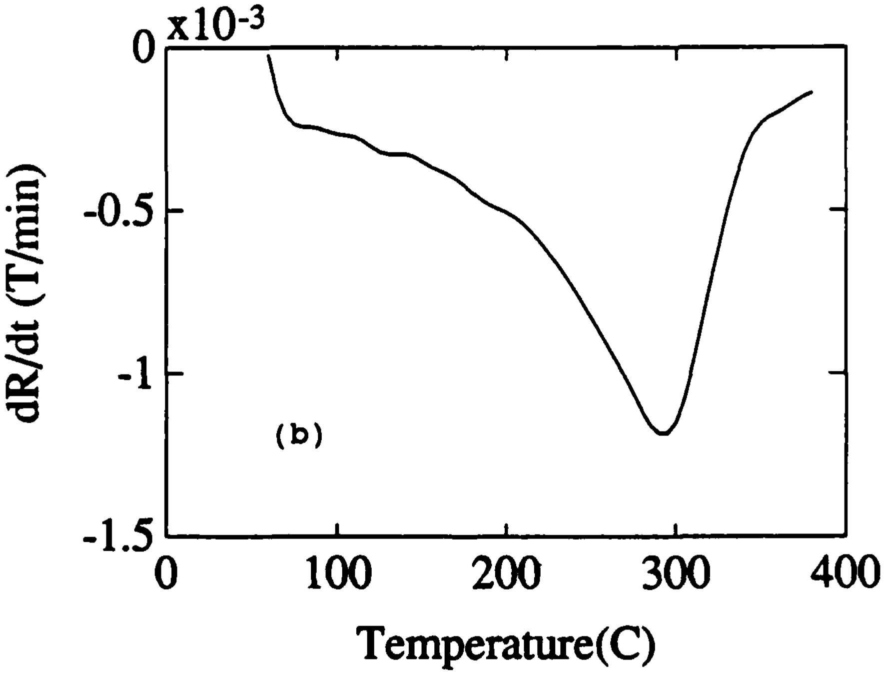


Figure 1b. Derivative of remanence versus time curve in Figure 1a.

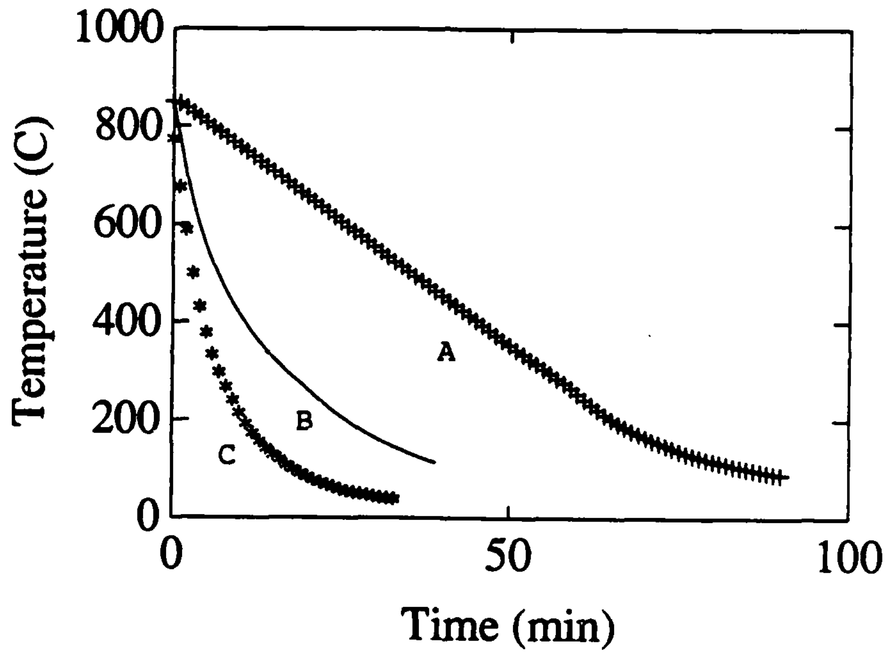
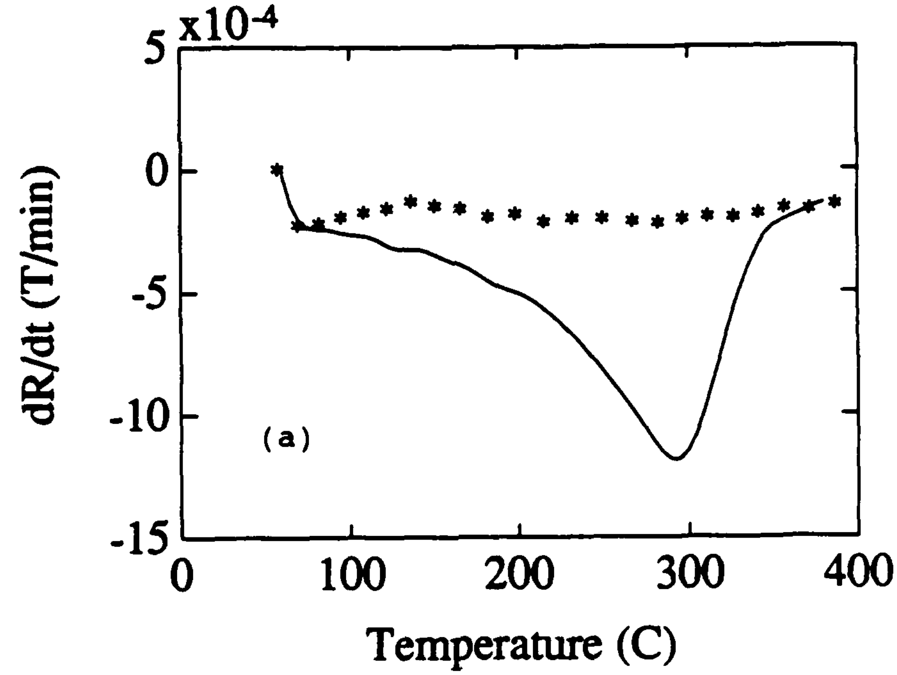
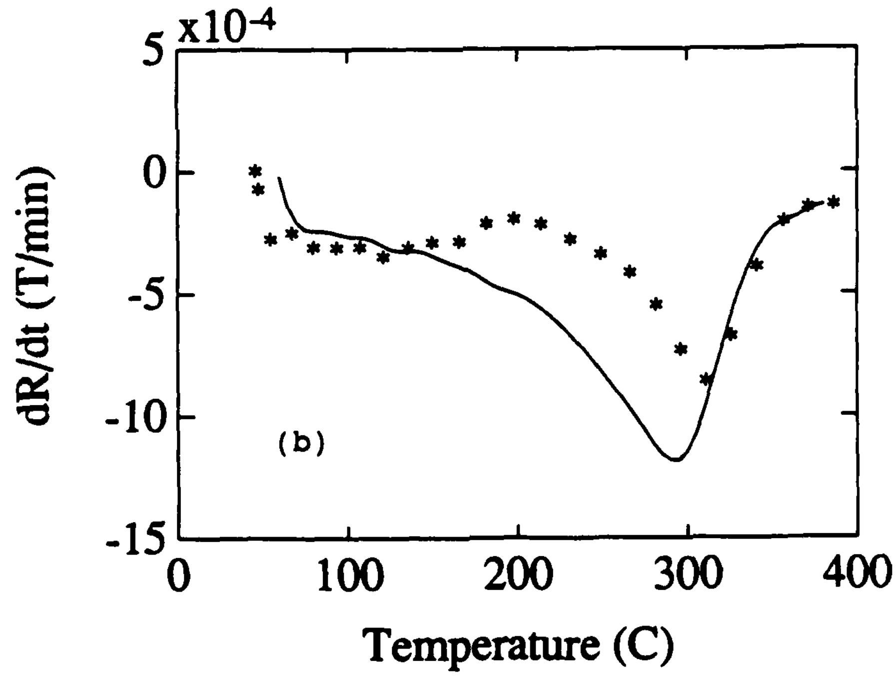


Figure 2. The three trial cooling rates (following austenitization) used in the present remanence thermal analysis study.

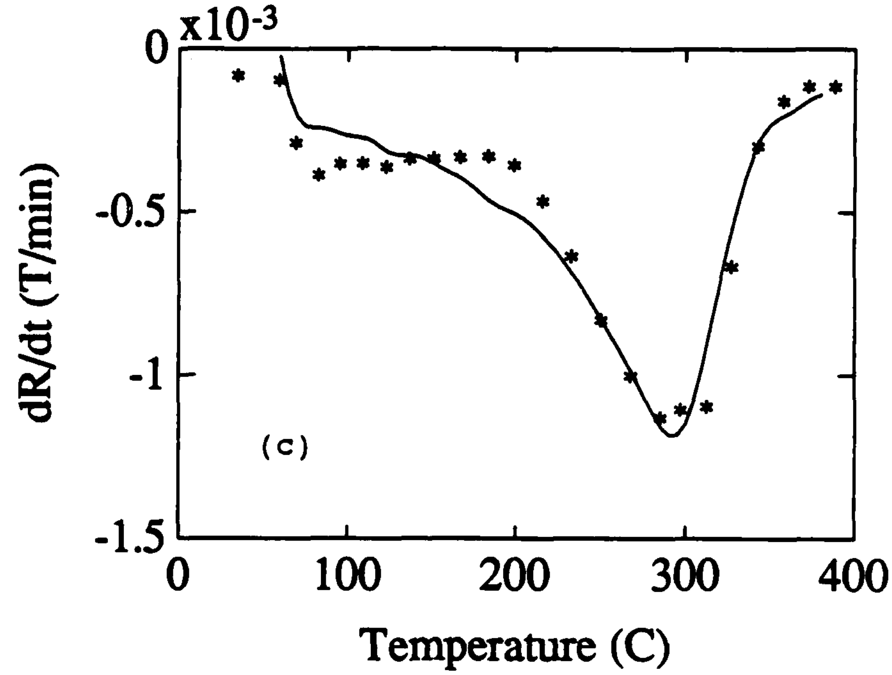


a. Cooling path B in Figure 2 followed by one hour temper at 600°C.

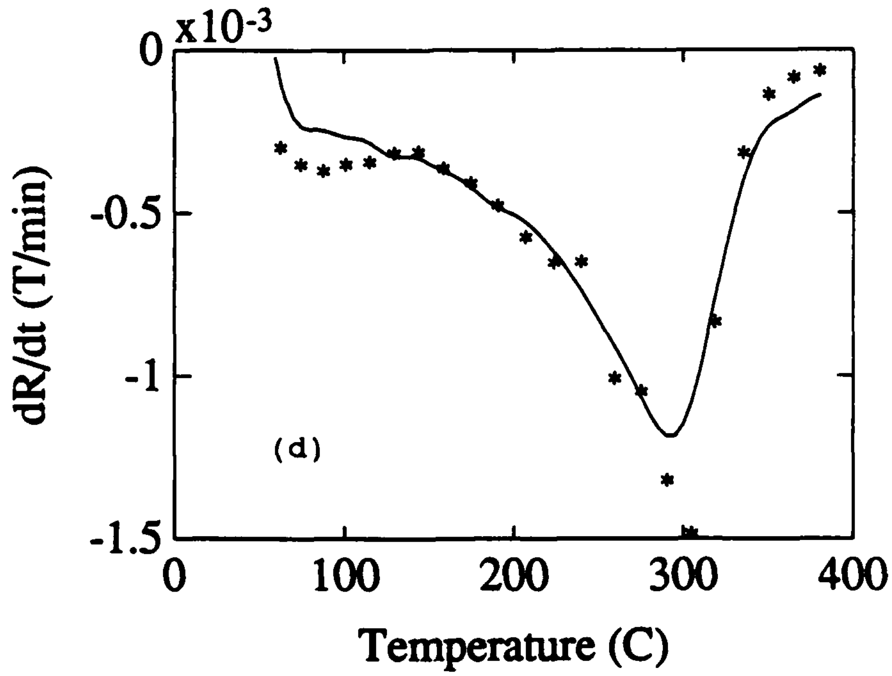


b. Cooling path A in Figure 2. No temper.

Figure 3. Comparison of as-received and laboratory thermal cycles with austenitization at 850°C followed by various cooling paths to room temperature.



c. Cooling path B in Figure 2. No temper.



d. Cooling path C in Figure 2. No temper.

Figure 3. Continued

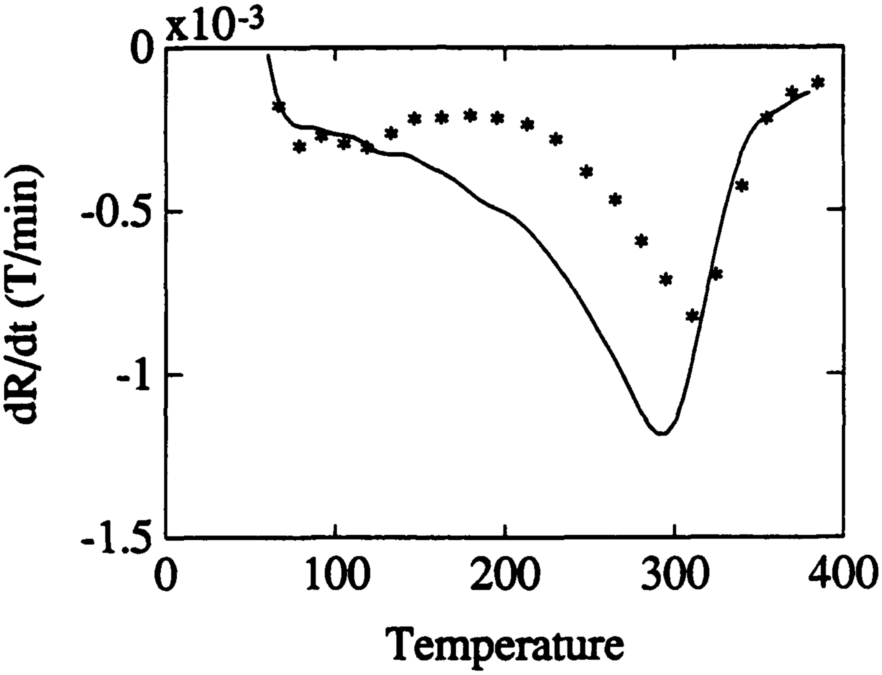


Figure 4. Comparison of as-received and laboratory thermal processing with austenitization at 950°C followed by cooling approximately along intermediate cooling path B in Figure 2. No temper.

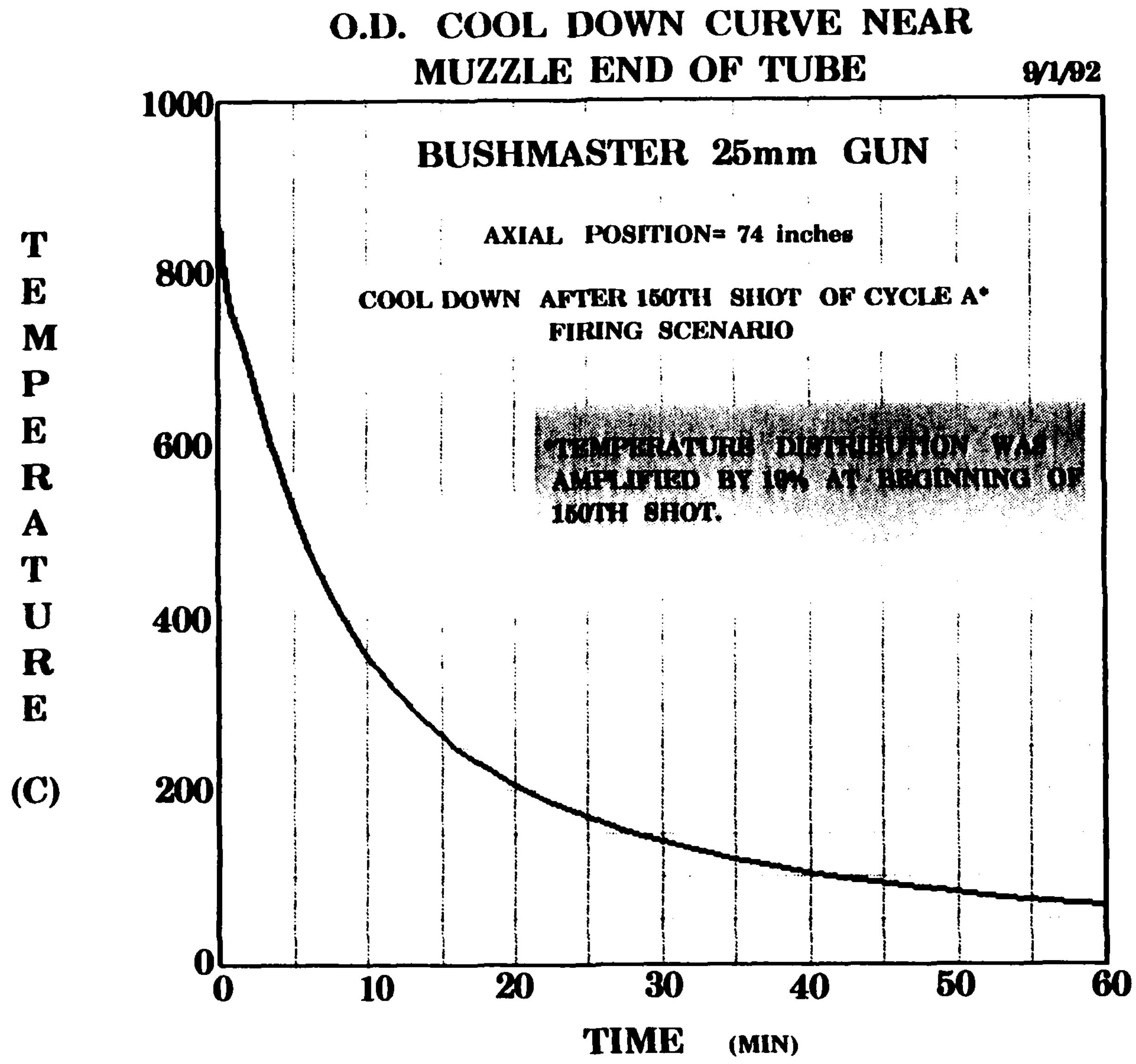


Figure 5. Calculated cooling path for the muzzle end of a Bushmaster barrel after the standard test firing schedule.

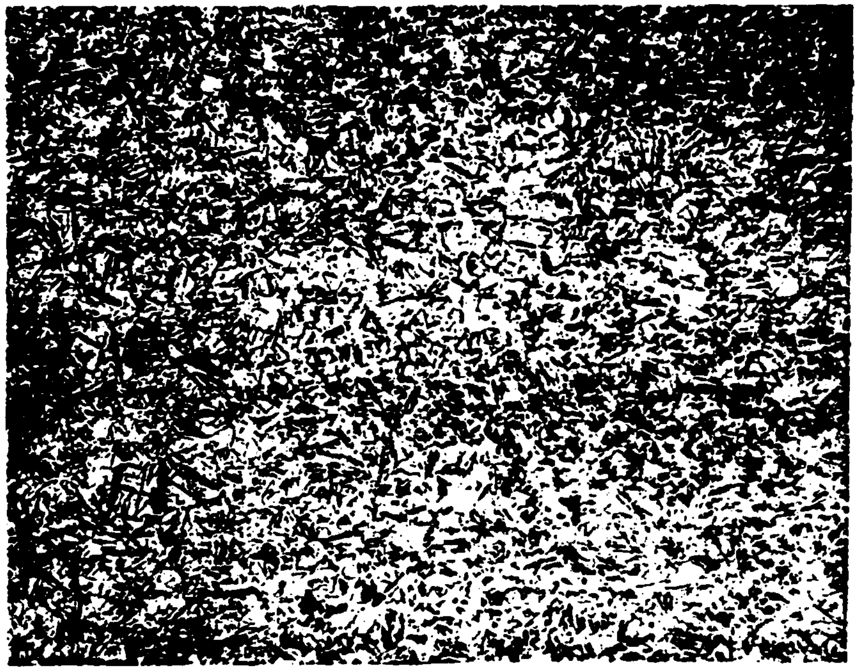


Figure 6. Photomicrograph of a section of the muzzle end of Bushmaster barrel SN 12373. Specimen is from an area adjacent to the specimen used in the remanence test. (500X)

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