Calculation of Hardness Using High and Low Magnetic Fields

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Abstract. Areas of increased hardness, or hard spots, are a great concern to the safe operation of high pressure gas pipelines, since they are more susceptible to hydrogen induced cracking (HIC). Utilizing the material effects on magnetic hysteresis, we will examine the ability to calculated hardness by comparing flux signals at high and low applied fields to B-H hysteresis curves that are a function of hardness. A finite element model will be used to generate flux signals from regions with known magnetic properties in order to evaluate the theoretical feasibility of the technique. A discussion of empirical results will address practical issues of implementation.

Introduction

For the past four decades magnetic flux leakage (MFL) technology has been used for inline inspection of gas and oil pipelines to detect and size metal loss anomalies. Corrosion is not the only detrimental anomaly that can be inspected using MFL as changes in material properties of steel also affect their magnetic characteristics. Recently their have been efforts to prioritize mechanical damage [1][2] and hard spots [3][4] using high magnetizing fields and low, or residual, fields. The success of these techniques ultimately relies on the magnetic hysteretic response of the steel involved.

The focus of this paper is determining the hardness of a hard spot caused by rapid quenching during the manufacturing process. Hard spots are of great concern because in high strength steels under high pressure, as in gas pipelines, they are susceptible to hydrogen induced cracking (HIC). We designed a finite element model using ANSYS 9.0 that will predict the MFL of a hard spot with a known hysteresis at different applied levels of magnetization. As the magnetic response of the material is not the only effect on the MFL signal, we modeled three different depths with two different geometries. An inverse model can be designed from a forward model that adequately covers the space defined by hard spot geometry and hysteresis.

1. Hard Spot Hysteresis

Hard spots from quenching are primarily martensitic in nature. There is very little data in the public domain that adequately correlates the BH curves to the hardness of martensitic steels. We were then forced to develop an analytic model to generate hysteresis curves from the known properties of pipeline steels listed in the U.S. Department of Transportation study [5] done in 1998. As this paper's goal is to develop a forward model using finite element analysis this analytic model is sufficient for our present purpose.

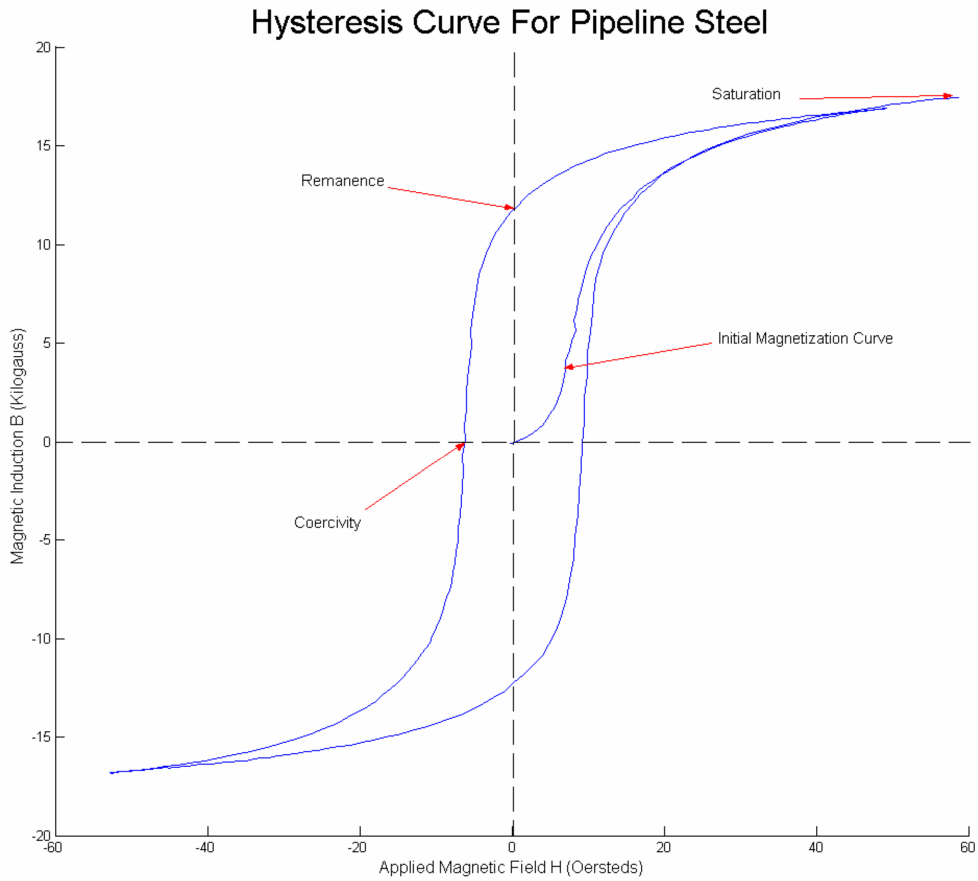

Figure 1: B-H curve for a typical sample of pipeline steel.

There is a strong correlation between hardness and coercivity [5], but saturation and remanence have a stronger chemical composition dependence, so we took a subset of the data that showed a correlation. We made linear fits of coercivity, remanence, and saturation to hardness and used these values to define the hysteresis curves. We looked at modeling the hysteresis curves with sigmoid, arctangent, and error functions but their modeling of the "knee"[1] portion of the hysteresis curve was not adequate. The Langevin models the knee region well but is completely determined by two parameters and does not give physically reasonable saturation values for the coercivities and remanences we are examining. Finally we went with the natural logarithmic fit:

$$\alpha \cdot \ell n(H) + \beta . \qquad (1)$$

Because of the singularity of the logarithm at H=0, we must shift the outer loop over by the coercivity (H_c) so that the remanence (B_r) occurs at H_c.

$$\beta = B_r - \alpha \cdot \ell n(H_c) \qquad (2)$$

The saturation value (B_s) occurs at $H_c + H_s$, where H_s is the applied field that reaches saturation. Solving for α gives

$$\alpha = \frac{B_s - \beta}{\ell n(H_c + H_s)}, \qquad (3)$$

which combined with eqn. 2 gives

[1] The knee region is the nonlinear region connecting the linear region near coercivity and the linear region near saturation.

$$\alpha = \frac{B_s - B_r}{\ell n\left(\frac{H_c + H_s}{H_c}\right)} \quad (4)$$

and

$$\beta = B_r - \frac{(B_s - B_r)\cdot \ell n(H_c)}{\ell n\left(\frac{H_c + H_s}{H_c}\right)}. \quad (5)$$

We used eqn. (1) for the initial magnetization as we were not so concerned about what happened in this region, but need it for the initial load steps to saturate the steel. The demagnetizing loop is just the translation this loop by $\pm H_c$.

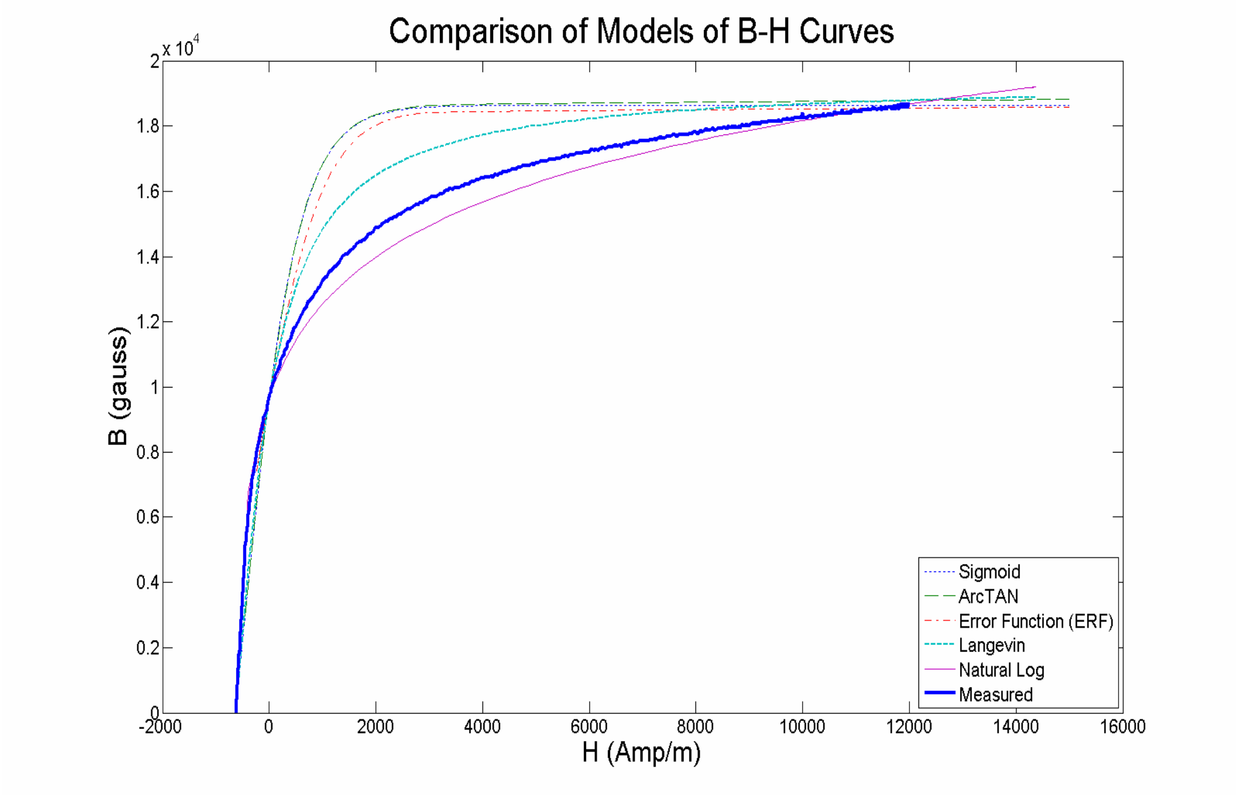

Figure 2: Simple analytic models of the outer magnetization loop of the B-H curve for pipeline steel

2. Finite Element Modeling

The geometry that we choose was a region of hardened steel on the surface of a pipe with a 30 inch outer diameter and .375" wall thickness. Since this was just a survey study to explore the feasibility of distinguishing the different materials we kept our control variables to a minimum. For hardness, we used the analytic model developed in section 1 to generate the BH curves for 180, 275, 350 and 450 Brinell, with the 180 Brinell used for the nominal pipeline steel and the other three for hard, harder and hardest spots respectively. Since hard spots are generated in the manufacturing process, the rolling of the steel gives them a circumferential aspect, so we examined two circumferential geometries, 3" long by 12" wide and 6" long by 12" wide, with three differing depths: 1/5 , 2/5, and 3/5 of the pipe wall thickness. There were 18 different models using these control parameters.

Table 1. Control Parameters for FEM

Thickness	Aspect	Hardness
1/5 wall thickness (.075")	3"L x 12"W	450 Brinell
2/5 wall thickness (.150")	6"L x 12"W	350 Brinell
3/5 wall thickness (.225")		275 Brinell

The finite element model (FEM) needed to be designed so that the magnetization would start out with the materials in their virgin state and step the applied field up the anhysteretic curve until both materials were effectively saturated. The applied field was then stepped down until it went a little past coercivity. This was done using a multi-step method that solved the model at an applied magnetization level and used this solution as the initial value for the next magnetization. The process used the usual iterations associated with repetitive analyses requiring 3D representation of the problem domain using symmetry, with attendant restrictive assumptions, and judgement on boundary conditions that can contain the model size yet adequately represent the physics.

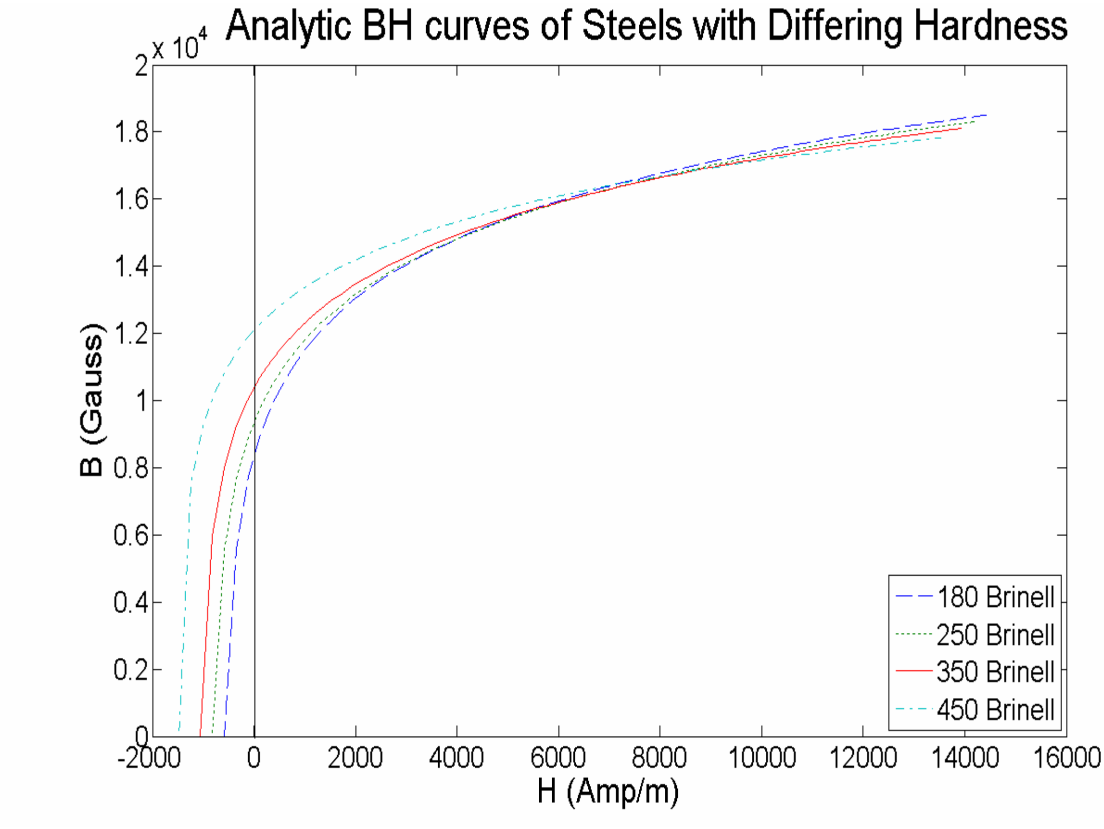

Figure 3: BH curves of different hardnesses generated for natural logarithmic fit to extrapolated measured data fro the GRI study of pipeline steels.

Initial modeling considered a complete pipe section with the embedded hard spot magnetized by a traditional MFL magnetizer configuration consisting of permanent magnets and a high permeability core. The FEM was an edge flux formulation using ANSYS element SOLID117 whose degree of freedom is the edge flux. This method resulted in huge problem sizes and computational burden.

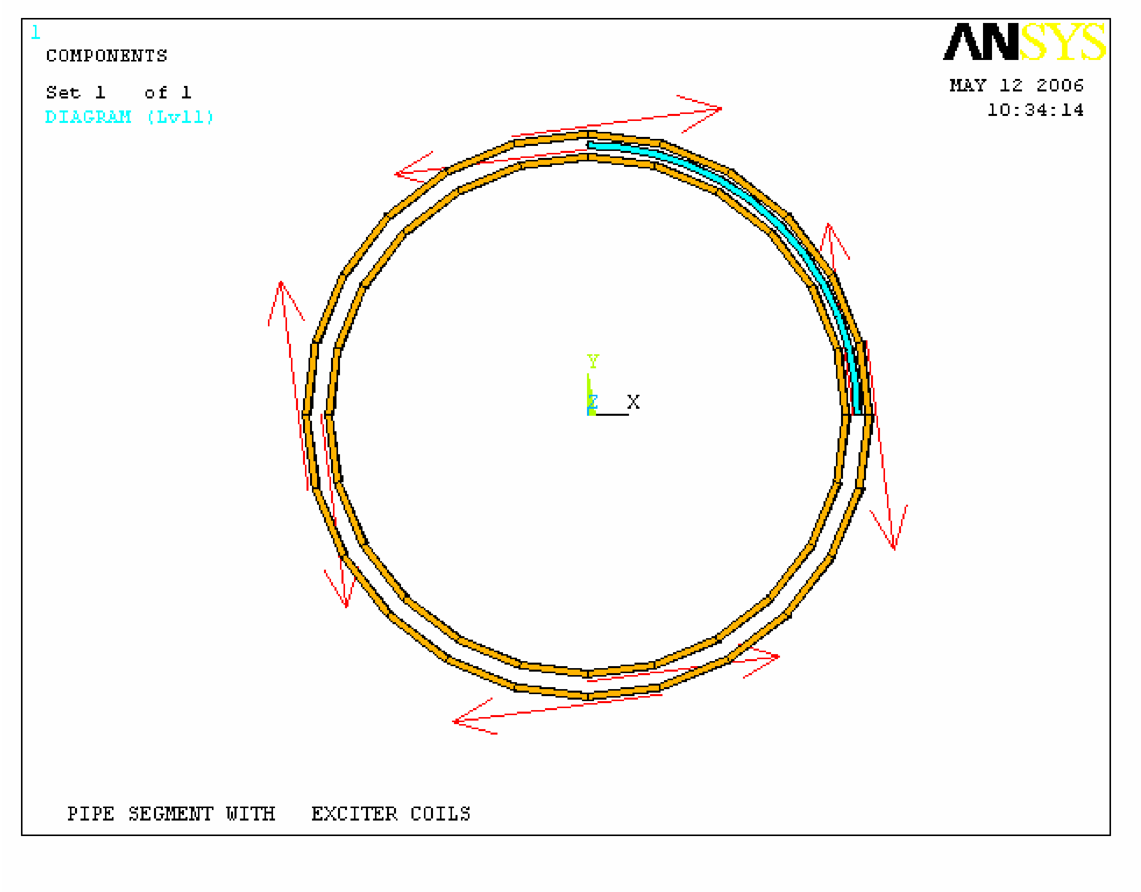

Figure 4: Finite element model of the steel pipe (aqua) embedded between two coils (orange) with oppositely oriented currents. The two opposing coils produce a homogenous field perpendicular to the page in the region between them.

To make the model more tractable we eliminated the burden of modeling the magnetizer and used symmetry. Since the crux of the modeling is the behaviour of the hard spot embedded in the surrounding pipeline steel, how the field enters the steel is not important as long as uniformity at region of interest is maintained. Future design of an optimal hard spot tool, though, must include the modeling of the magnetizer. Our new design was a pipe imbedded in a long solenoid. This model can be modeled using the ANSYS SOLID96 scalar potential formulation. The magnetization is provided by the primitive element SOURC36. It is used to represent the current distribution in the model but is not included in the model; instead it is solved separately to calculate the H field intensities via Bio-Savart's law which are applied on the axial boundary conditions. The far circumferential field is modeled using the infinite boundary elements INFIN47.

This model was then ran for each of the parameters in table 1 for 23 load steps starting from 1000 amps to 40000 amps and back down to -4000 amps.

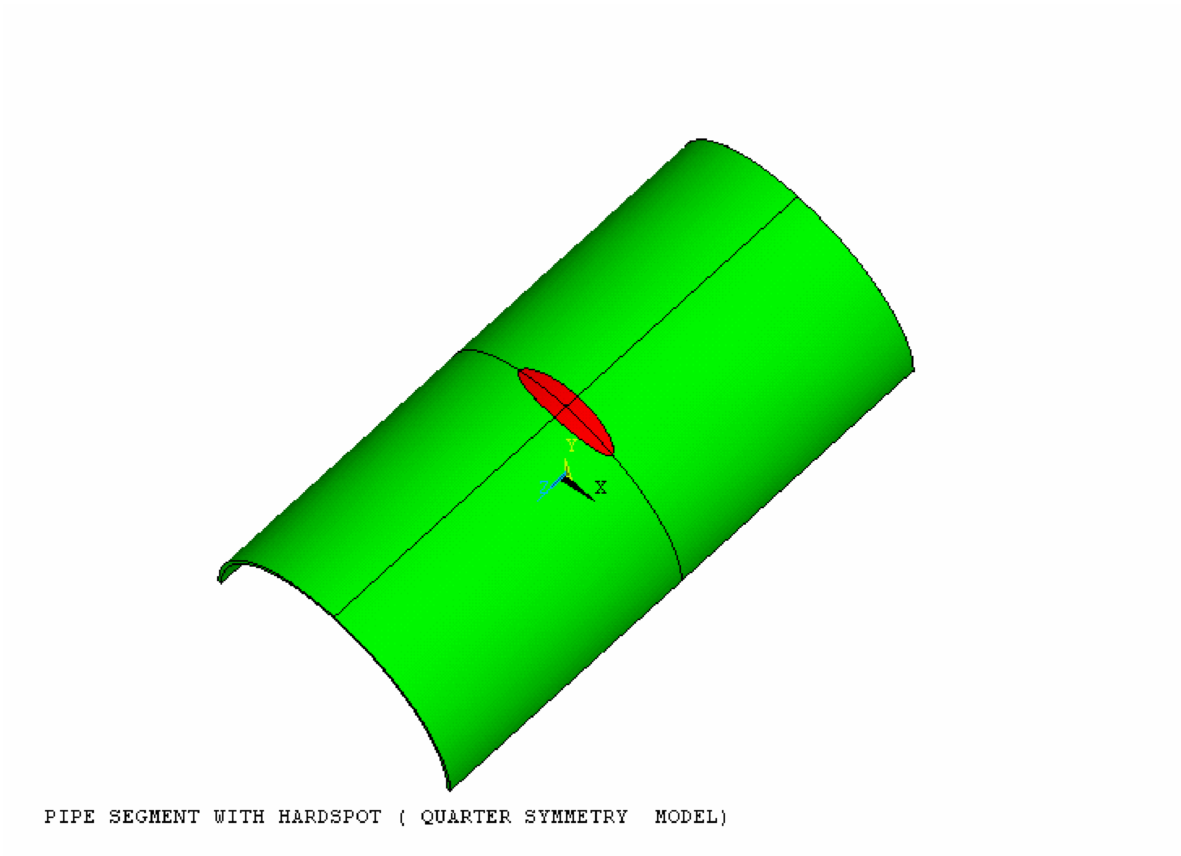

Figure 5: The pipe section (green) with circumferential hard spot (red). Only one quarter of the model needs to be solved with reflective boundary conditions on the cuts. Note that this model actually models two hard spots with the other one occurring 180 degrees on the other side.

3. Analysis

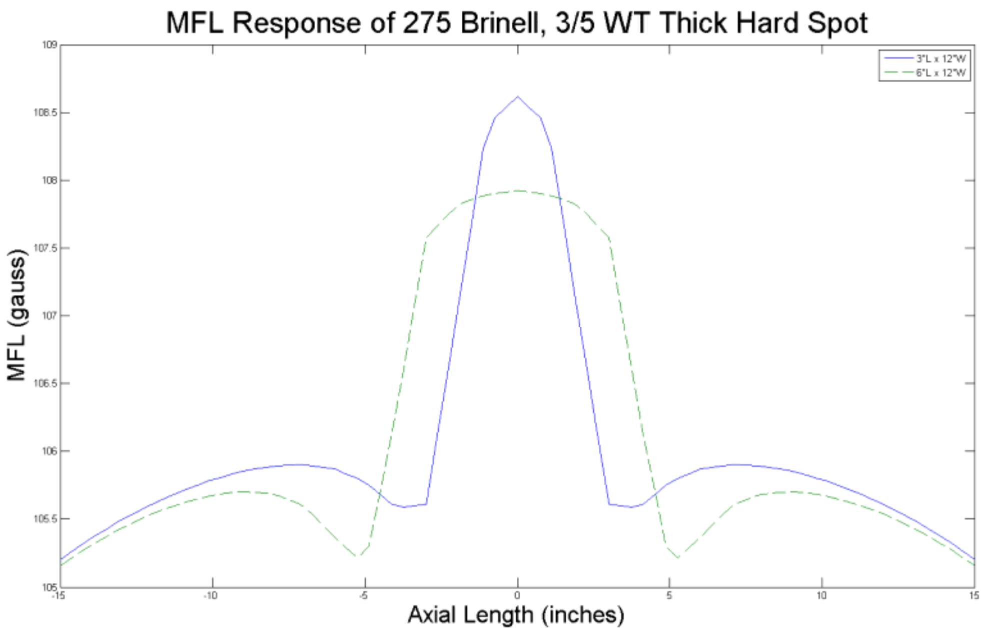

Figure 6: Comparison of a hard spot with different lengths.

We focused our analysis on the area that a hall sensor would measure data, a path one eight inch away from the inner surface of the steel. A typical signal is shown in Fig. 6. The slight decay at the ends is an artifact of the modeling. The model can not be too long or the computation time would become overburdening and the magnitude of the decay is much lower than the signals we analyzed.

The next stage of analysis was to take difference between the value of the signal in the center of the hard spot to the flux near the nominal pipe which we call the *peak to baseline*. Graphing these values for each stage of the applied magnetization, we can determine the effect of each of the parameters.

3.1 Planar Aspect

The circumferential aspect of the hard spot was found to not have a great influence on the amplitude of the peak to baseline value. There is a 2% - 7% change in signal amplitude between the 3" x 12" spot and the 6" x 12" spot.

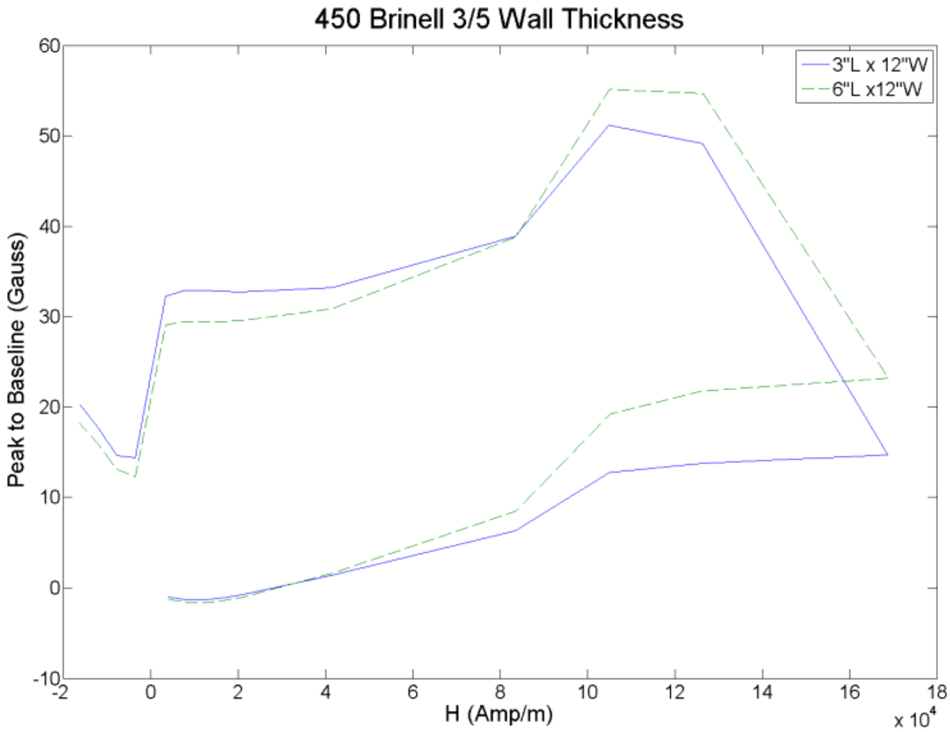

Figure 7: Plot of the MFL from hard spots with different lengths at each magnetization step.

3.2 Thickness

The thickness of the hard spot has a strong affect on the MFL signal. It ranges from 8% to 32% of the maximum signal.

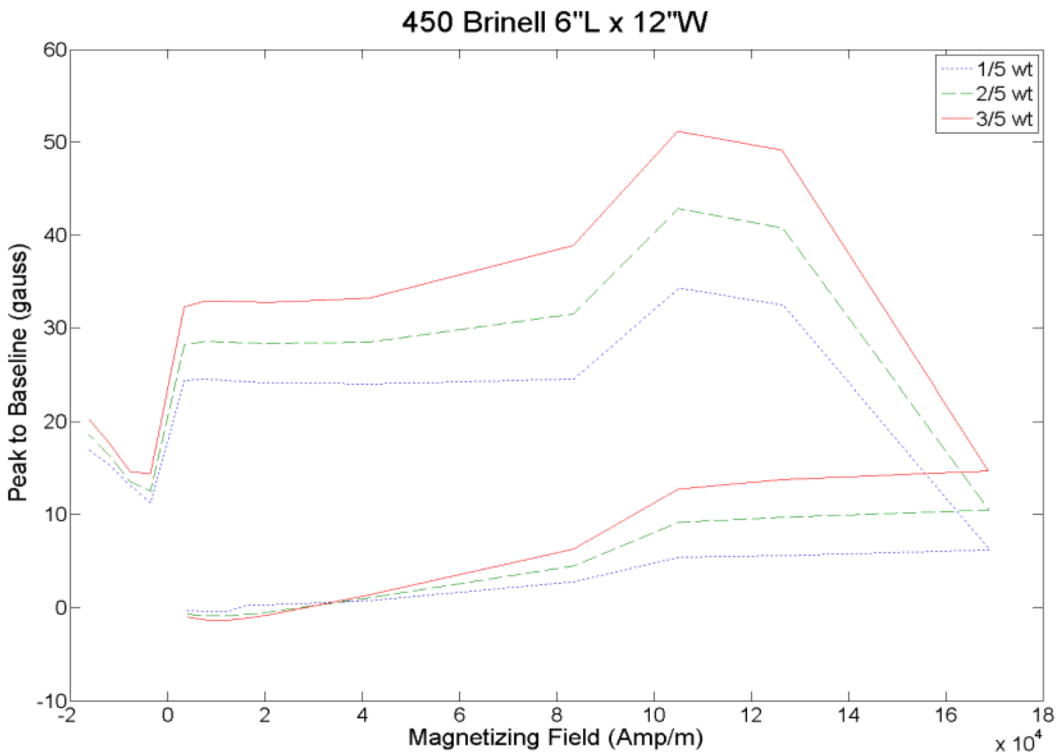

Figure 8: A plot of the MFL response for hard spots of different thicknesses.

3.3 Hardness

The hardness of the hard spot has the effect changing the signal by 8% to 35% over the range we measured.

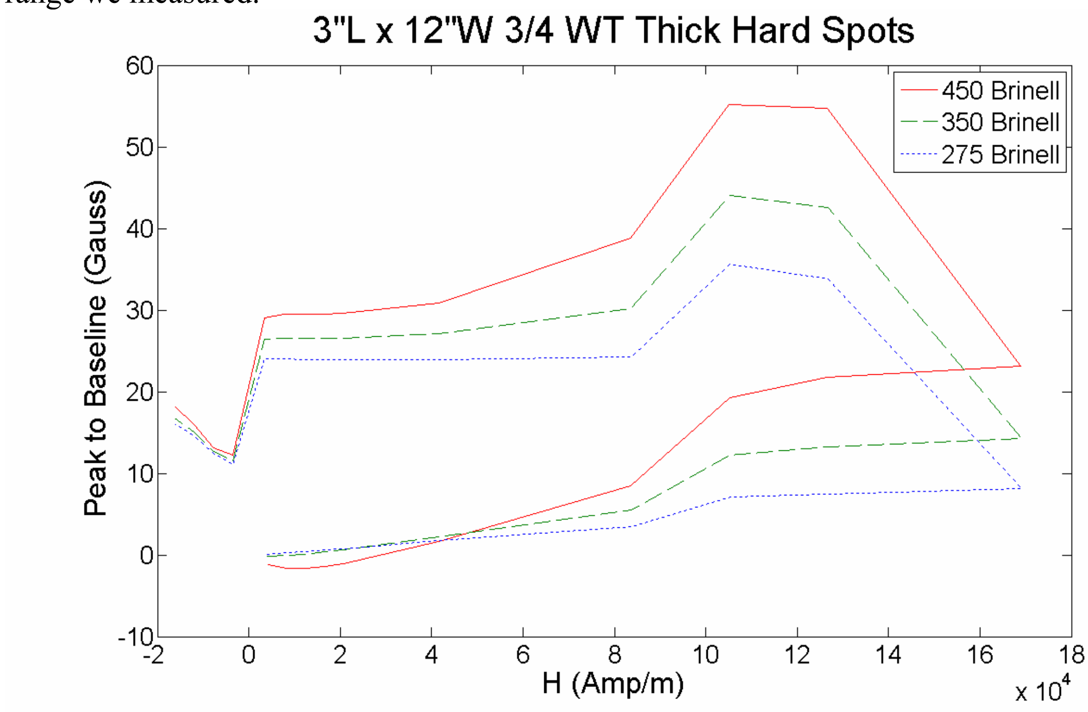

Figure 9: A plot of the MFL response for hard spots of differing hardnesses.

Conclusion

The results of our modeling show that there is a dramatic jump in the MFL response after reaching saturation values and decreasing the field. We should make finer steps in the applied field in this region to see if it is an artifact of the modeling or not. The conclusions of our models are severely limited by the lack of measured BH curves for the martensitic pipeline steels. The BH curves of our models did not show a large divergence as shown in figure 3, but there is an assumption that the remanence will increase with hardness. Another detail is the cross over point near saturation where the harder materials become less permeable. If the jump in amplitude is a result of the coercive nature of the steel then its high correlation with hardness can be used to calculate the hardness.

Geometry can be derived by the profile of the signal (i.e. length and width). The main influence on signal amplitude is then thickness and hardness. If there is a strong correlation between these two variables, that is harder spots are also thicker, then it should be possible to develop algorithms to correlate hardness to MFL signals.

Future work will require more data on the BH curves of martensitic steels and would have to take into account the actual magnetizer being used.

References

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[5] Nestleroth J. and Crouch A. "Variation of Magnetic Properties in Pipeline Steels." U.S. Department of Transportation, DTRS56-96-C-0010