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CALCULATION OF THE TEMPERATURE DEPENDENCE OF MAGNETIC PERMEABILITY FOR STRUCTURAL STEELS

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Introduction (1)

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Because it affects the depth (δ) to which an induced current penetrates.

Introduction (2)

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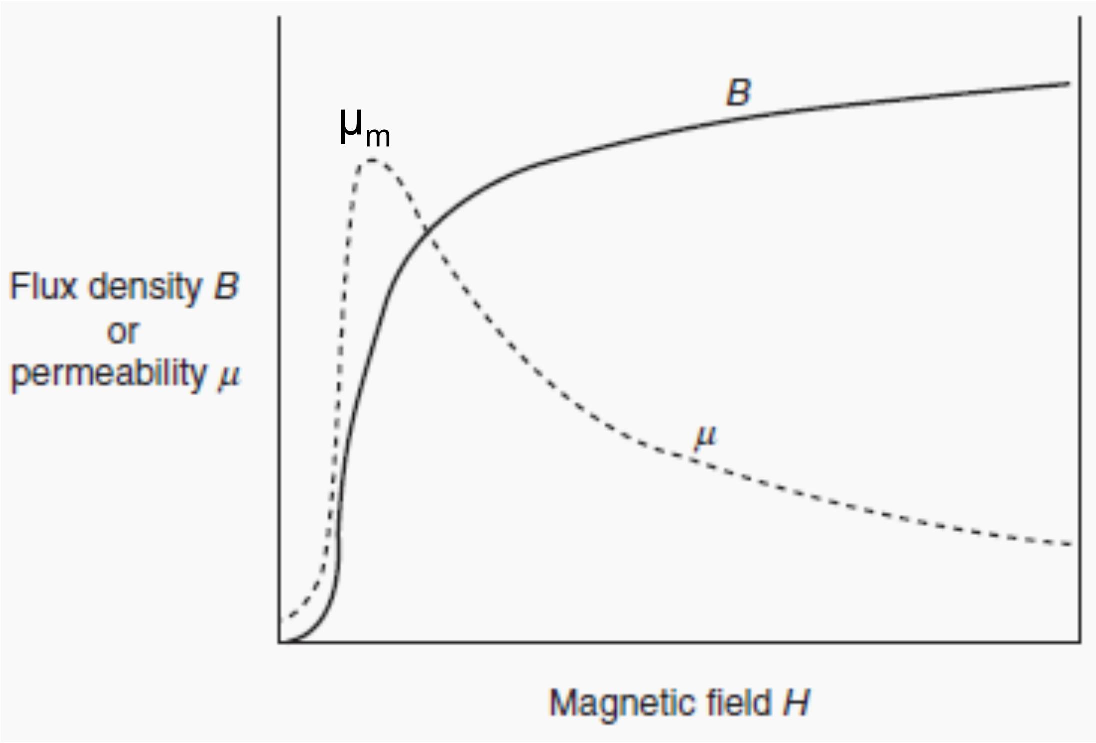
This has a serious effect on the electrical efficiency of a coil and insufficient water cooling of the coil can lead to premature coil failure

What is permeability

Permeability is a measure of how induction (B) changes with an applied magnetic field (H) and the value given in papers and reference materials is usually the maximum permeability (μ_m).



μ_m
B
Flux density B
or
permeability μ
μ
Magnetic field H

What is permeability

It is also usual for μ_m to only be measured at room temperature. Very few measurements have been made for its temperature dependence which is critical to a process such as induction heating.

Question

Is it possible to obtain a simple model for the calculation of μ_m, and its temperature dependence, that is applicable to wide variety of steels?

Model

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This can be demonstrated using B/H hysteresis loops

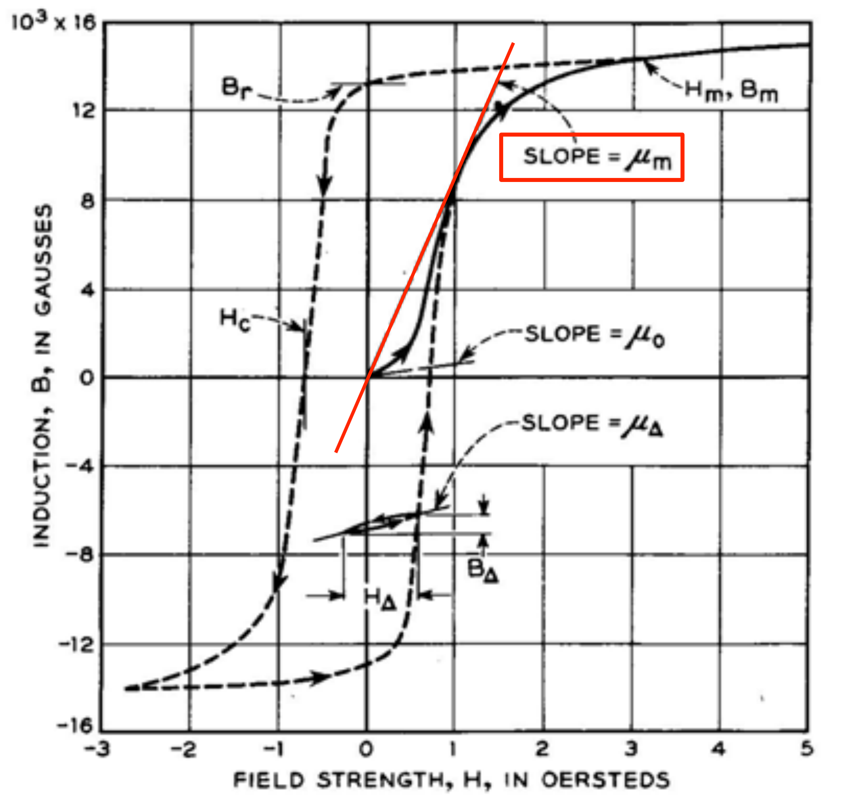
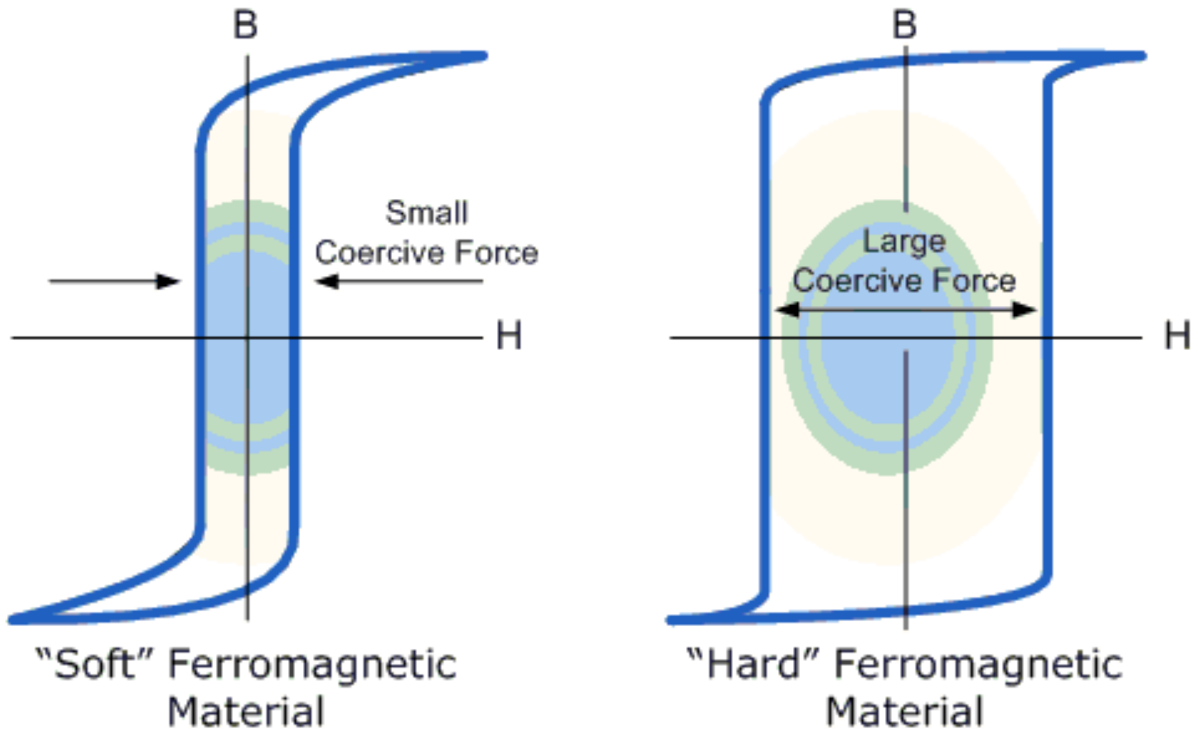


Fig. 1–4. Magnetization curve (solid) and hysteresis loop (dotted).


B
Small
Coercive Force
H
"Soft" Ferromagnetic
Material
B
Large
Coercive Force
H
"Hard" Ferromagnetic
Material

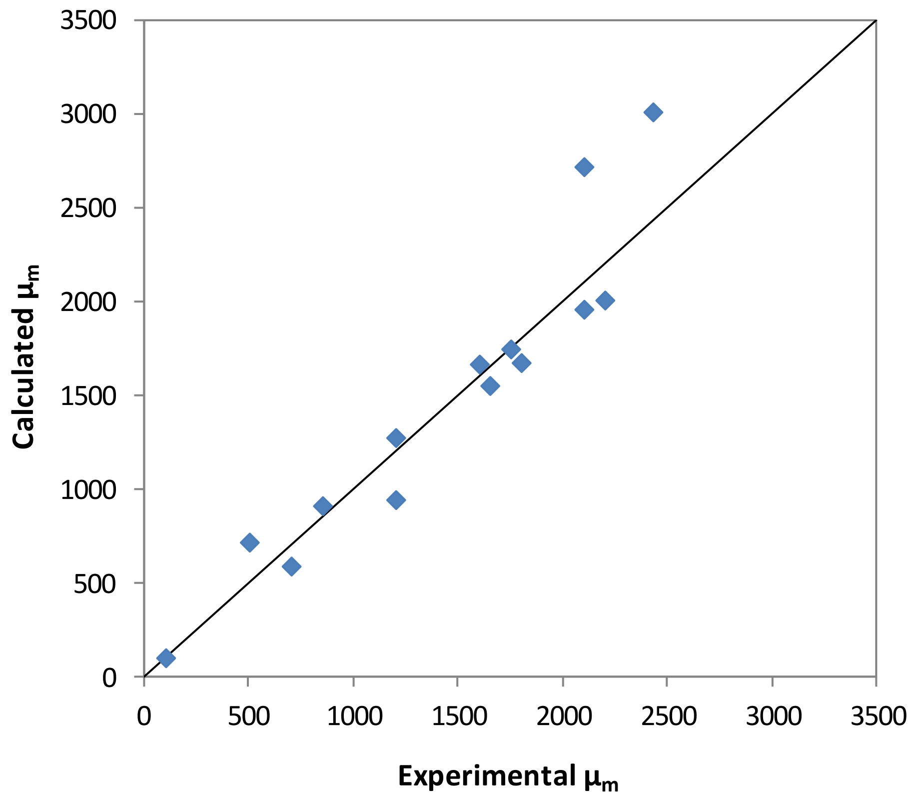
Model

In practice, μ_m is found to be proportional to saturation magnetisation (B_s) and the coercive force (H_c) such that

$$\mu_m = \mu_m^0 + (B_s / 4H_c)$$

where $\mu_m^0 \sim 1$

Calculated vs. experimental μ_m

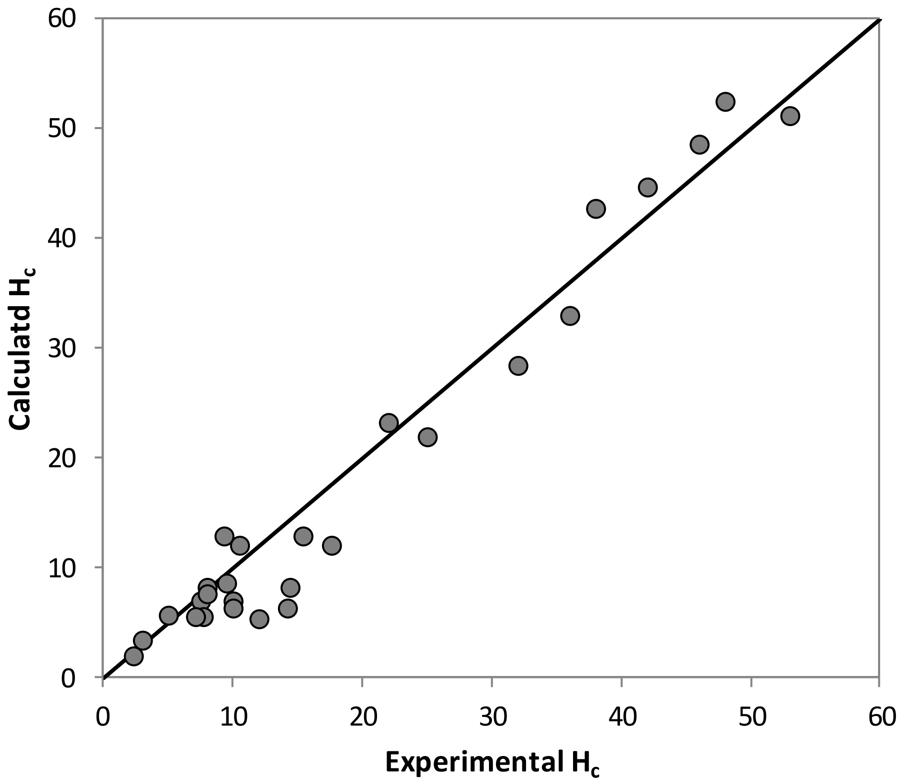


Model

The value of B_s for pure Fe is well known and can effectively be treated as a constant unless alloy levels become very high.

It is then possible to calculate H_c from hardness, which means that μ_m can be directly estimated using an easily measured and well known property for steels

Calculation of H_c



Temperature dependence of μ_m

Once the value of μ_m at room temperature is obtained, we now need to evaluate its temperature dependence.

It is well known that the permeability falls drastically on approaching the Curie temperature (T_c) and becomes unity above T_c

Temperature dependence of μ_m

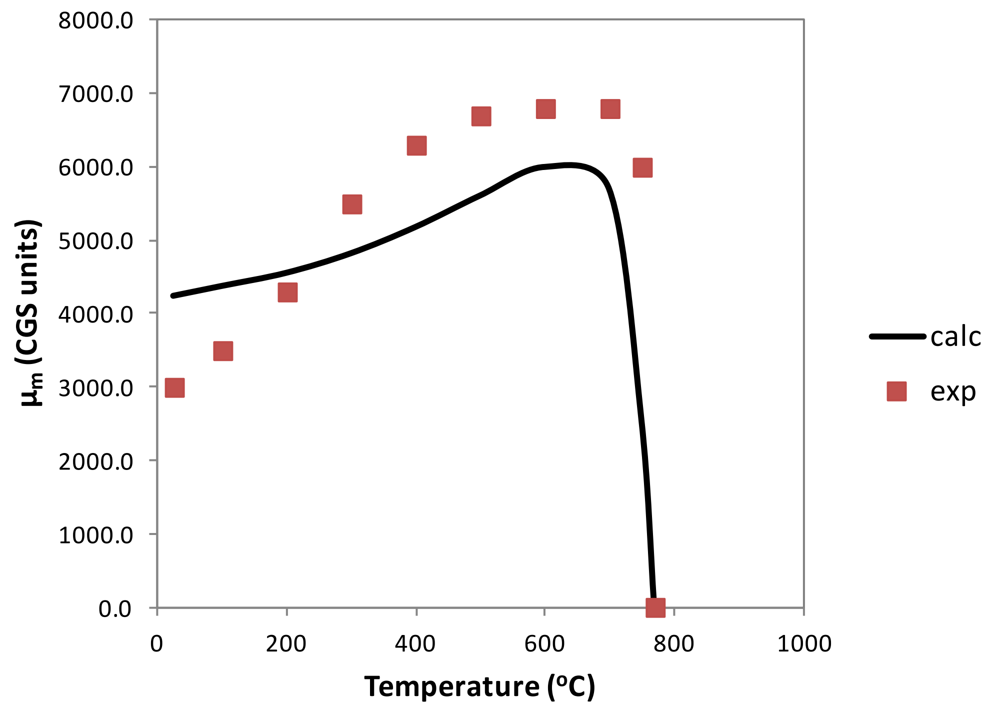
The variation of B_s with temperature can be expressed as a function of $(1 – [T/Tc]^6)$ *

While H_c can be expressed as a function of $(1 - [T/Tc]^3)$ ¤

Which means that μ_m can now also be calculated as a function of temperature

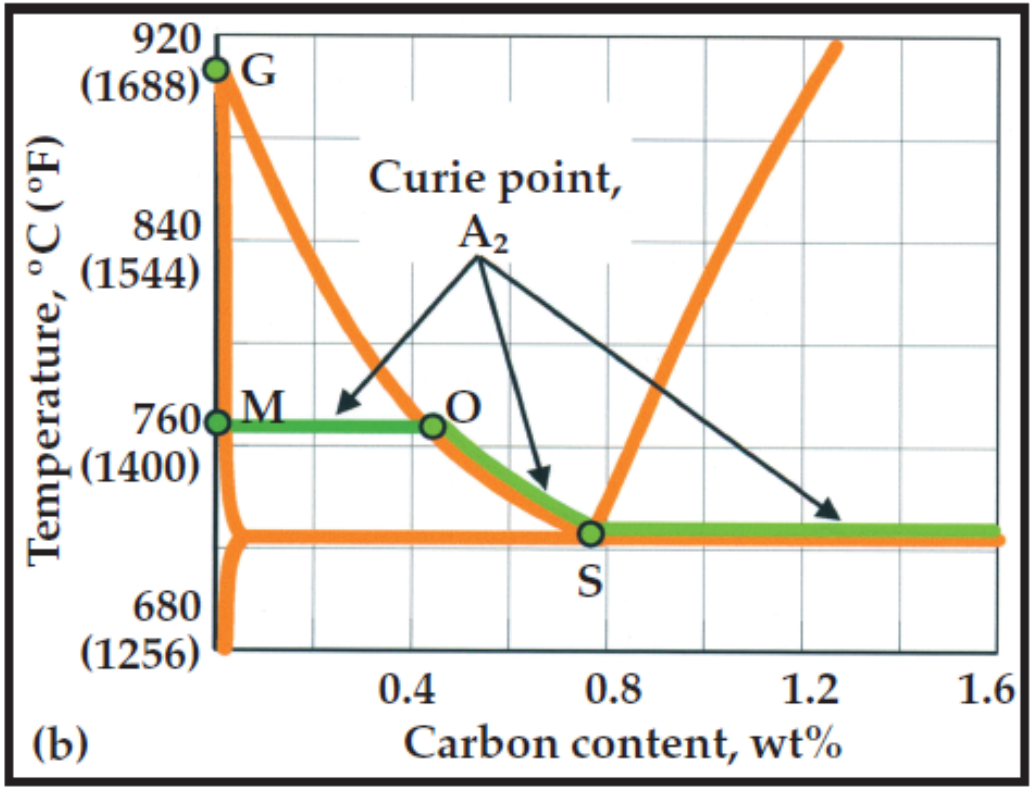
* A.P. Miodownik, *CALPHAD*, 1 (1977), 133
¤ F.C.Schwerer et al, *Acta Met.*, 26 (1978) 579

Comparison with measured permeability for iron



Temperature dependence of μ_m

In an steel the temperature dependence is also governed by the amount austenite that may form below T_c.


920
(1688)
G
Curie point,
A2
840
(1544)
M
O
760
(1400)
S
680
(1256)
0.4
0.8
1.2
1.6
Temperature, °C (°F)
Carbon content, wt%
(b)

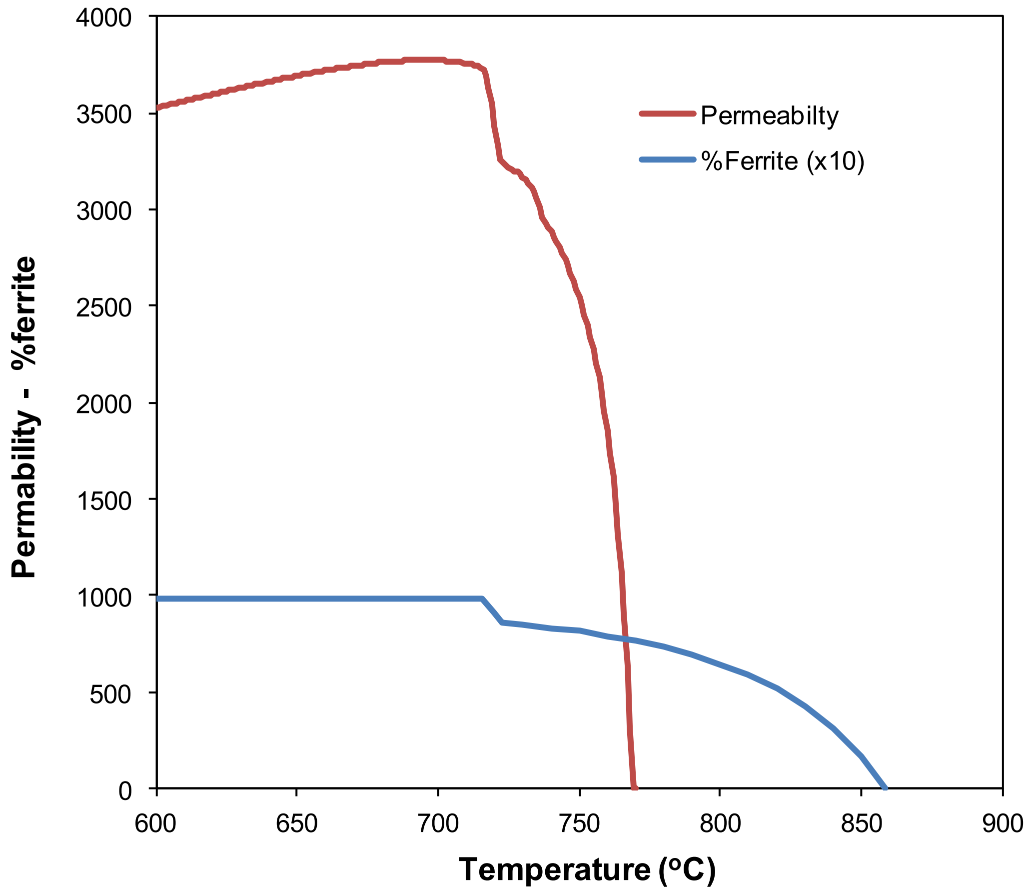
Temperature dependence of μ_m

The previous picture is a little confusing in that, while T_c for ferrite might remain constant in the ferrite+austenite two phase region, the permeability will also be controlled by the fraction of austenite that is formed. In which case,

$$\mu (T) = \mu_F (T) . V_F(T) + \{1- V_F(T)\}$$

Where V_F is the volume fraction of ferrite and μ_F is the permeability of ferrite.

Ferrite content vs permeability for a low C steel



There is now enough information to calculate the temperature dependence of μ_m for a steel with knowledge of only two pieces of information

1. The hardness of the steel

and

2. The volume fraction of austenite and ferrite

Note: the amount of ferrite below the A_1 temperature needs to be adjusted to take into account the amount of cementite that is formed

The hardness of the steel is readily measured, while the volume fraction of austenite and ferrite can be calculated from a re-austenisation module developed for the software programme
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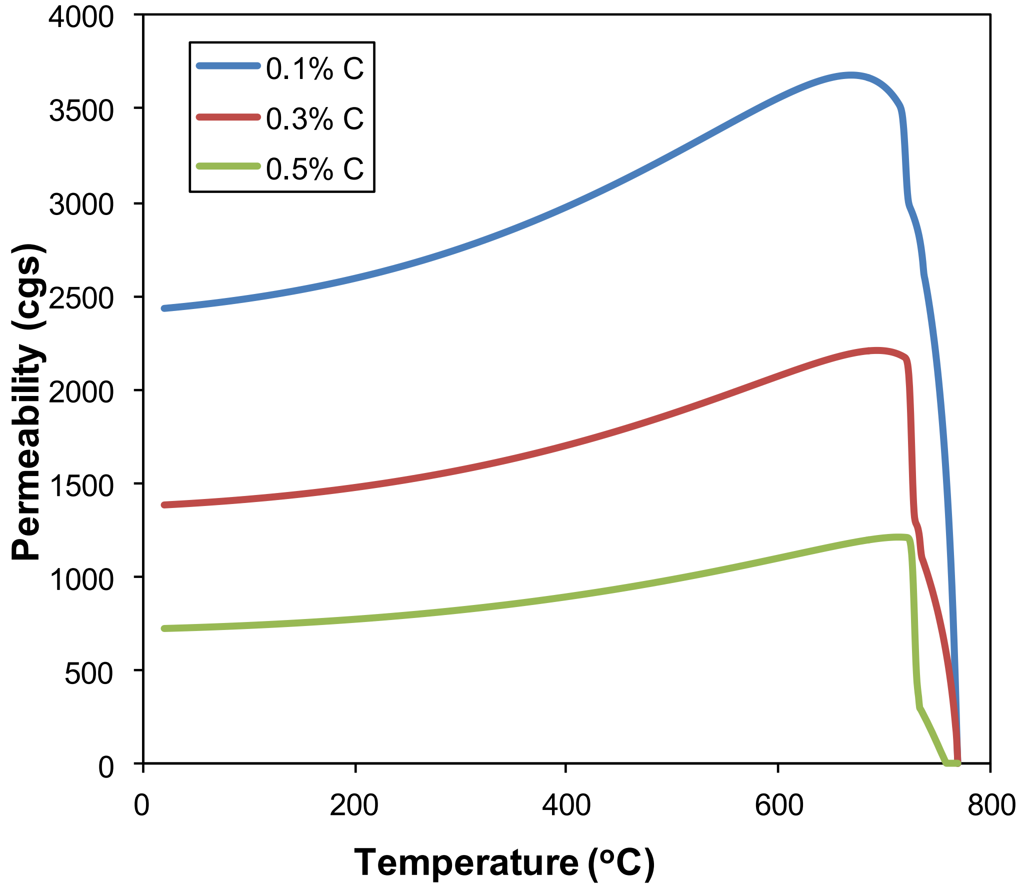
and which has been described in a previous presentation at the current conference.

Effect of Carbon Content on μ_m of normalised steels (heating rate = 1 C s^{-1})



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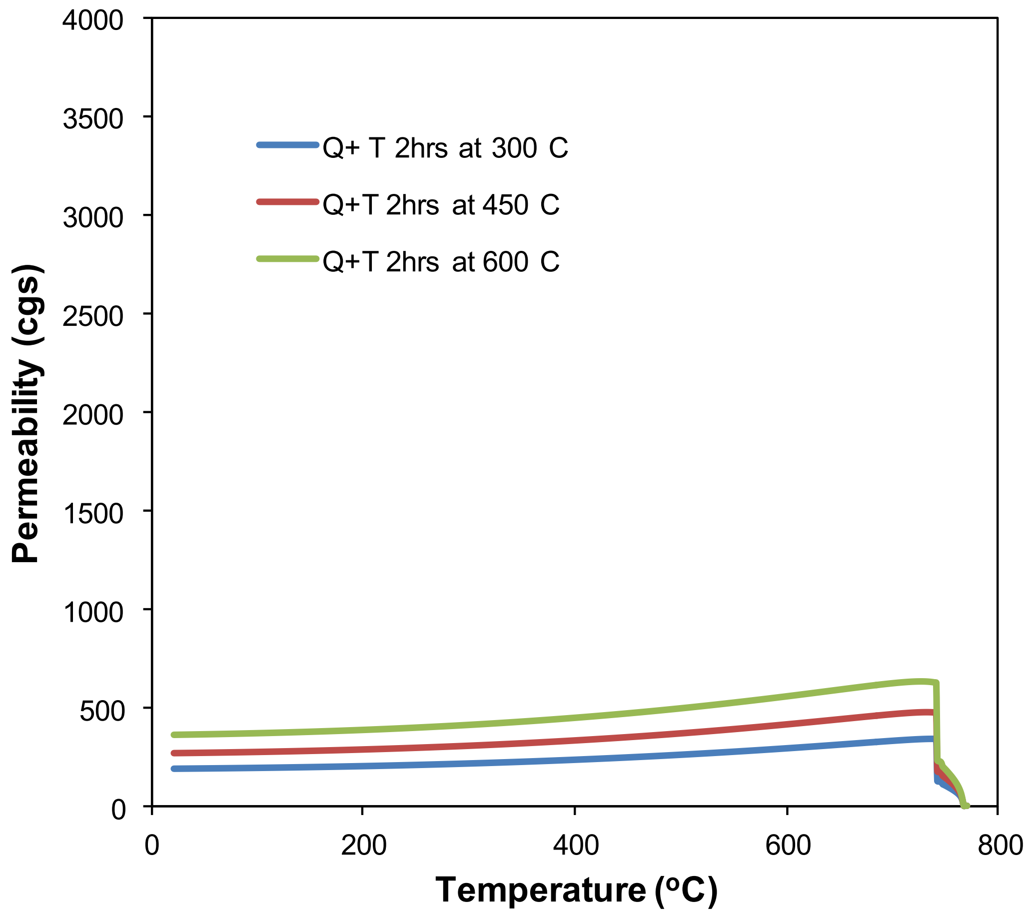
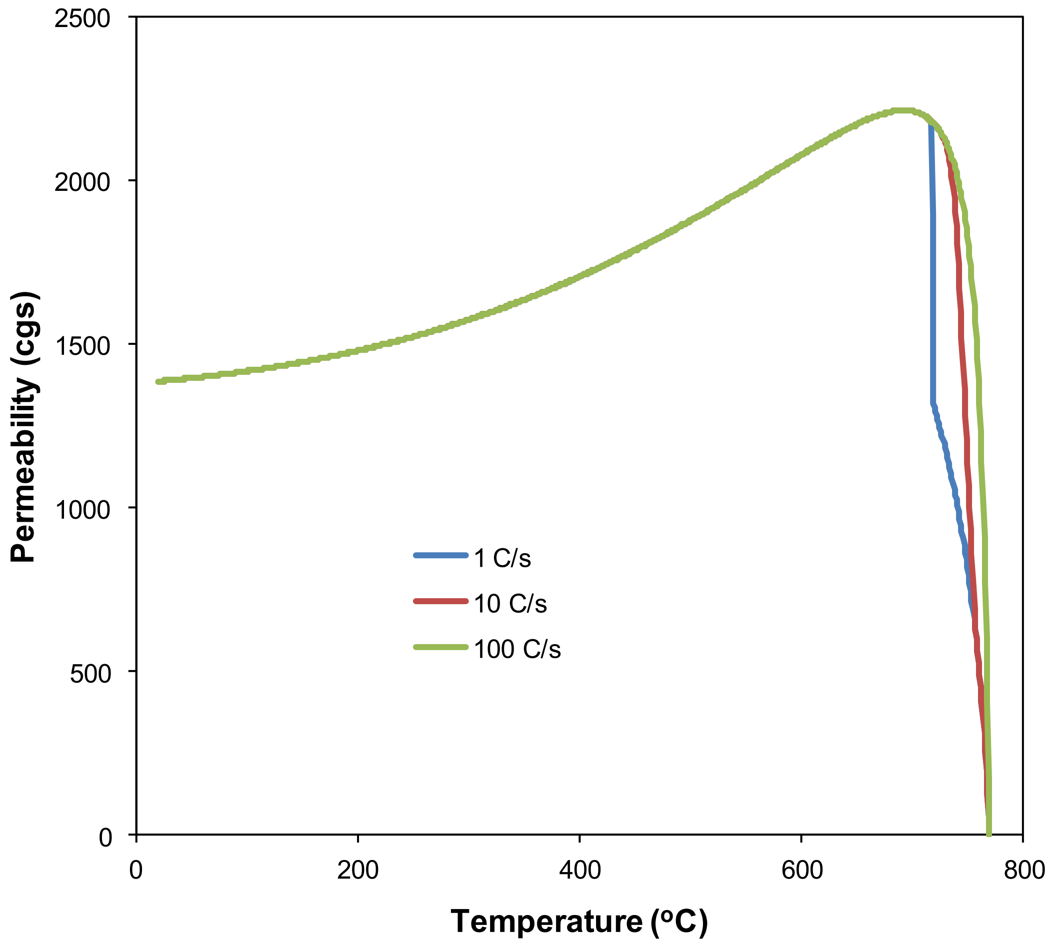
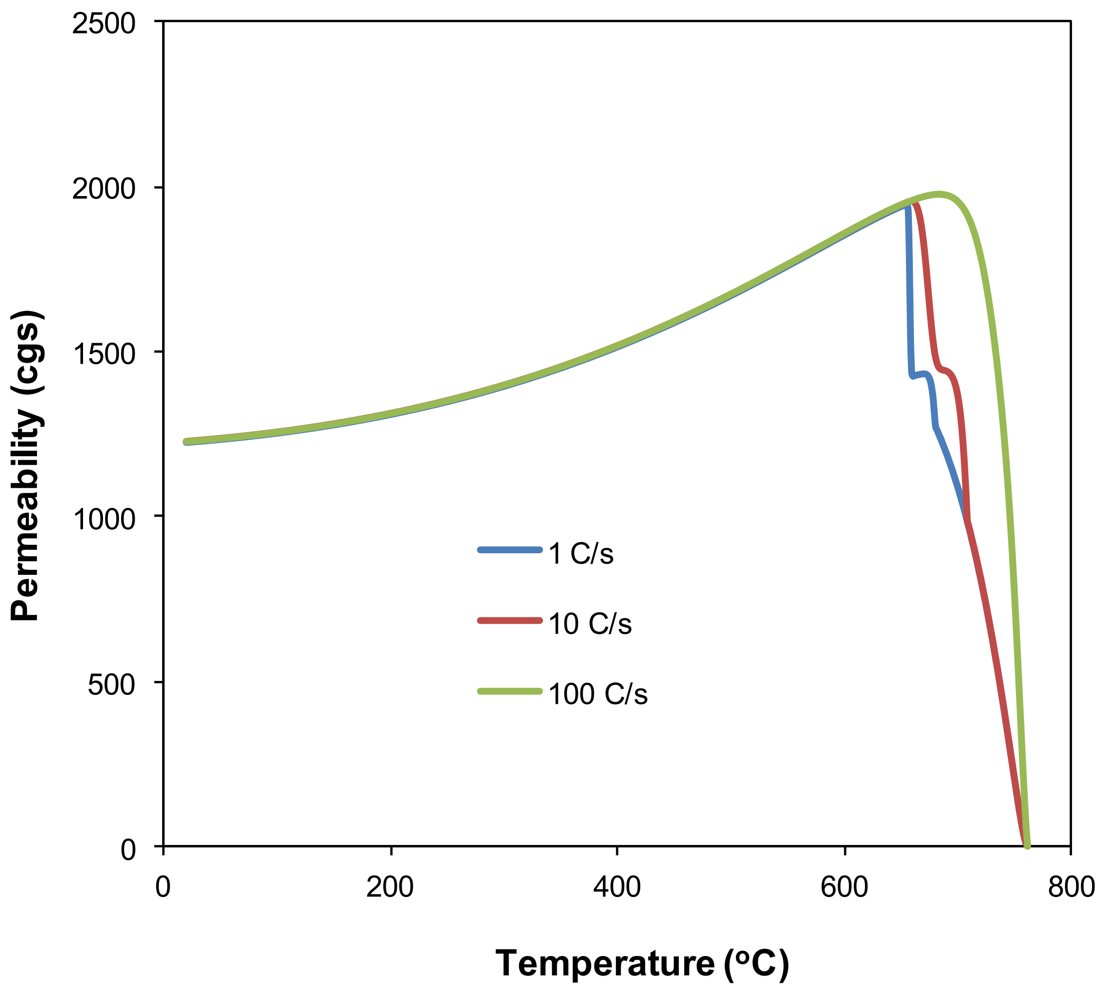
Effect of Hardness resulting from tempering of a 4140 steel (heating rate = 0.1 C s^{-1})



Effect of Heating Rate for a 1030 steel



Effect of Heating Rate for a normalised 4815 steel



Summary and Conclusions

1. A model has been developed to calculate the permeability of steels as a function of temperature

2. The permeability rapidly changes close to the Curie temperature of ferrite. It is also closely linked to the amount of ferrite present in the steel at temperature.

Summary and Conclusions

3. The permeability is strongly dependent on the room temperature hardness/strength of the steel.

4. While changes in permeability occurring as a result of changes in the amount of ferrite above the A_1 are significant, they are less significant than those resulting from the hardness/strength of the steel.