

LOCATION SWANSEA

LEVEL 7

**EXAMINATION PERIOD
MAY 2015**

LLEOLIAD ABERTAWE

LEFEL 7

**CYFNOD ARHOLIADAU
MAI 2015**

MODULE CODE: M7X00725
Electromagnetic Methods

TIME: 2 HOURS

ANSWER ALL QUESTIONS

Formulae and Material Properties on last two pages

ANSWER ALL QUESTIONS

Question 1. Total Marks – 20

- a) With reference to induced eddy currents in a conductor, explain the skin effect and the effective depth of penetration. (6 marks)

Answer:

Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux, normally travelling parallel to the coil's winding with flow limited to the area of the inducing magnetic field.

Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil. Eddy current density decreases exponentially with depth.

This phenomenon is known as the **skin effect**.

The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases.

Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents.

The depth that eddy currents penetrate into a material is directly related to the frequency of the excitation current, the electrical conductivity, and magnetic permeability of the specimen.

The depth of penetration decreases with increasing frequency and increasing conductivity and magnetic permeability.

It is mathematically convenient to define the '**standard depth of penetration**' (δ) where the eddy current is $1/e$ (37%) of its surface value, and is given by:

$$\delta_{mm} = \frac{661}{\sqrt{f\mu_r\sigma}}$$

Where,

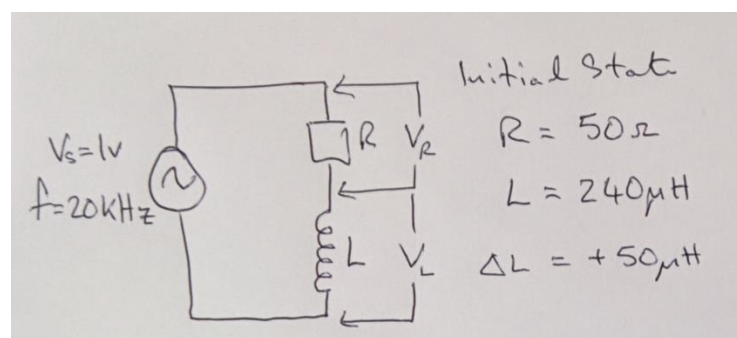
δ = Standard Depth of Penetration (mm)

f = Test Frequency (Hz)

μ_r = Relative Permeability (dimensionless, = 1 for non-ferrous materials).

σ = Electrical Conductivity (% IACS)

- b) The following bridge circuit is typically used to determine and display the impedance variations in a conventional eddy current system. When the eddy current probe (L) is brought close to a conducting surface it's inductance value increases from an initial value of $240\mu\text{H}$ by $50\mu\text{H}$. Determine the measured voltages at both instances and illustrate how this could be displayed on a complex impedance plane. (6 marks)



Answer:

Solution: $X_L = 2\pi fL = \frac{48}{5}\pi \Omega$.

Initial State

$$Z_L = 0 + jX_L = 0 + j\frac{48}{5}\pi = \frac{48}{5}\pi \angle 90^\circ \Omega$$

$$Z_R = 50 + j0 = 50 \angle 0^\circ \Omega$$

$$Z_T = 50 + j\frac{48}{5}\pi = 58.392 \angle 31.098^\circ \Omega$$

$$I = \frac{V_s}{Z_T} = \frac{110}{58.392 \angle 31.098^\circ} = 17.126 \text{ mA} \angle -31.098^\circ$$

$$V_R = I \cdot Z_R = 856.3 \text{ mV} \angle -31.098^\circ$$

$$V_L = I \cdot Z_L = 516.51 \text{ mV} \angle 58.902^\circ$$

Final State: $X_L = 2\pi fL = \frac{58}{5}\pi \Omega$.

$$Z_L = 0 + jX_L = 0 + j\frac{58}{5}\pi = \frac{58}{5}\pi \angle 90^\circ \Omega$$

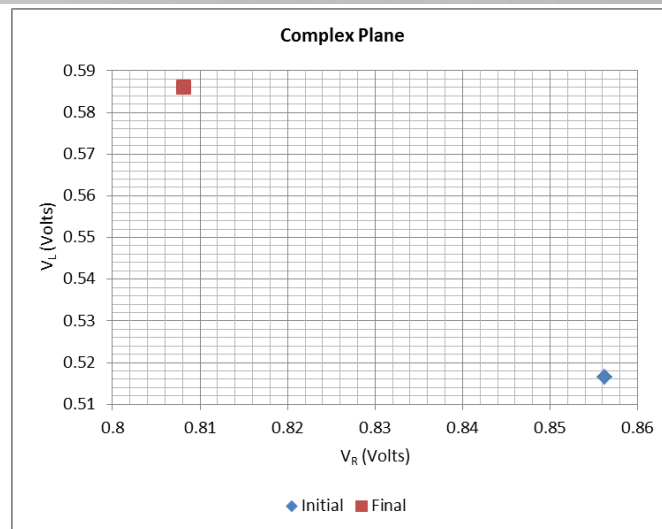
$$Z_R = 50 + j0 = 50 \angle 0^\circ \Omega$$

$$Z_T = 50 + j\frac{58}{5}\pi = 61.871 \angle 36.09^\circ \Omega$$

$$I = \frac{V_s}{Z_T} = \frac{110}{61.871 \angle 36.09^\circ} = 16.163 \text{ mA} \angle -36.09^\circ$$

$$V_R = I \cdot Z_R = 808.15 \text{ mV} \angle -36.09^\circ$$

$$V_L = I \cdot Z_L = 586.02 \text{ mV} \angle 53.91^\circ$$



- c) An eddy current test coil is used to inspect a copper component 1mm in thickness. Assuming 0.5mm as the standard depth of penetration required and that the conductivity of copper is 98.6 %IACS:

- i) Calculate the required test frequency. **(2 marks)**

Answer:

To determine the required test frequency, we need to re-arrange the depth of penetration formula:

$$\delta_{mm} = \frac{661}{\sqrt{f\mu_r\sigma}}$$

$$f = \frac{1}{\mu_r\sigma} \left(\frac{661}{\delta_{mm}} \right)^2$$

For copper, $\mu_r=1$

$$f = \frac{1}{98.6} \left(\frac{661}{0.5} \right)^2$$

$$f = 17.7 \text{ kHz to 3 dig. digits}$$

- ii) What would be the maximum phase difference between the induced near and far surface eddy currents? **(2 marks)**

Answer:

Using the phase lag equation:

$$\theta = \frac{x}{\delta} \times 57.3$$

At the near surface there is 0° phase shift, since this is our reference.

At 1mm ($2 \times \delta$):

$$\theta = \frac{1}{0.5} \times 57.3$$

$$\theta = 114.6^\circ$$

Therefore the maximum phase difference between the near and far surface eddy currents would be 114.6° .

- iii) If we were to increase the test frequency by an order of 2, what would the effects be regarding the depth of penetration and near and far surface phase differences? **(4 marks)**

Answer:

Using Test Frequency, $f = 2 \times 17.7\text{kHz} = 35.4\text{kHz}$,

$$\delta_{mm} = \frac{661}{\sqrt{f\mu_r\sigma}}$$

$$\delta_{mm} = \frac{661}{\sqrt{(35.4 \times 10^3) \times 98.6}}$$

$$\delta_{mm} = 0.354\text{mm to 3 dec. places}$$

At the near surface there is still a 0° phase shift, however, at the far surface the phase shift is calculated as:

$$\theta = \frac{1}{0.354} \times 57.3$$

$$\theta = 162^\circ \text{ to 3 sig. figures}$$

By increasing the test frequency by 2, we have increased the phase difference from 114.6° to 162° . However, by reducing the depth of penetration from 0.5mm to 0.354mm we have reduced our sensitivity to far surface indications exponentially.

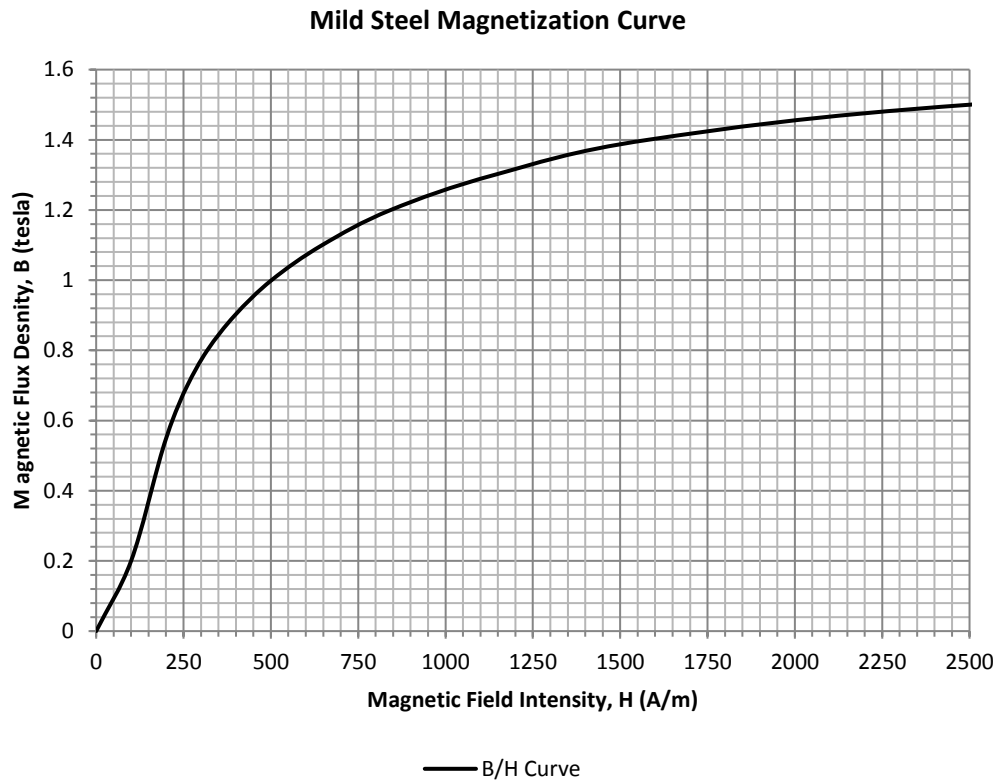
For example, for the first case where we have a test frequency of 17.7kHz, and $\delta=0.5\text{mm}$. Then 1mm is $2 \times \delta$, and therefore the eddy currents at this depth are approx. 13.5% of those at the surface.

In the second case, where the test frequency is 35.4kHz, we have $\delta=0.354\text{mm}$. This very roughly $\frac{1}{3} \times 1\text{mm}$, and therefore the eddy currents at the far surface are approx. 5% of those at the surface.

Question 2. Total Marks - 20

With reference to the following mild steel normal magnetization curve:

- i) Identify and explain the 4 distinct regions used to describe the changes to the materials magnetic domains. **(6 marks)**



Answer:

Field intensity values from 0 to 100 A/m, a slow rise due to 'reversible growth'.

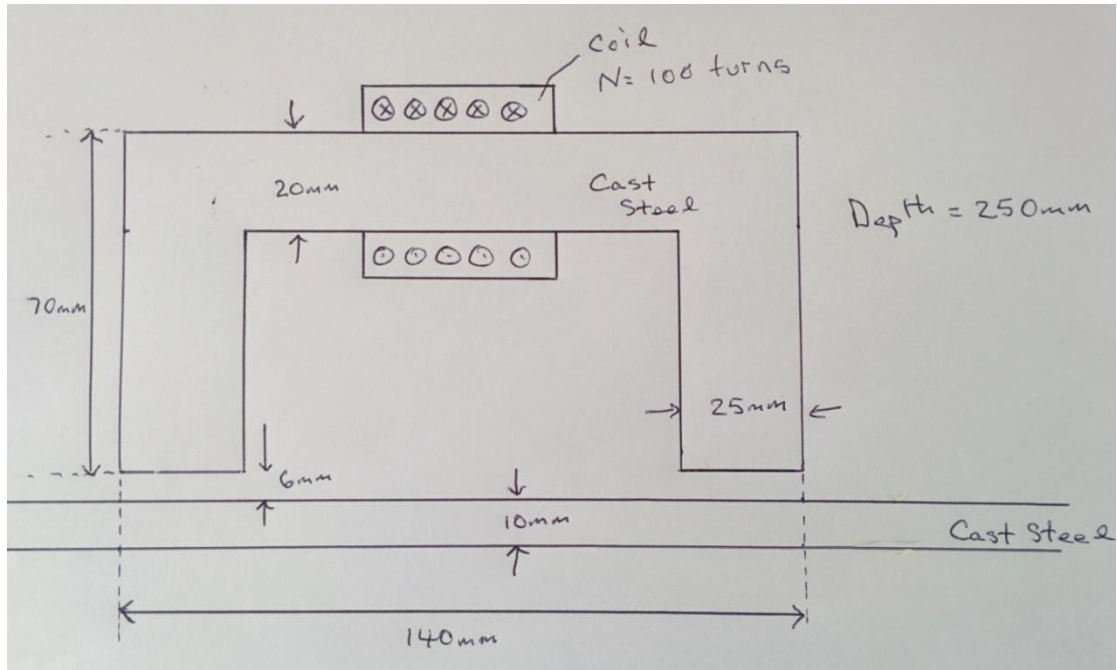
Field intensity range 100A/m to approx 250A/m, a longer, fairly straight, stretch representing 'irreversible growth'.

Field intensity range 250A/m to approx 1500 A/m, a slower rise representing 'rotation'.

Beyond 1500A/m, an almost flat region corresponding to paramagnetic behaviour and then μ_0 - the core can't handle any more flux growth and has saturated.

- ii) The electromagnetic yoke illustrated in the figure below is used as part of an MFL inspection system to scan petrochemical storage tank floors, determine the current required in the coil to achieve a flux density in the cast steel plate of 1.2T. Assume no leakage flux and no fringing of the flux occurs in the air gaps.

(14 marks)



Answer:

Assuming no leakage flux:

For $B_{plate} = 1.2T$

Φ in circuit $= B_{plate} \times A_{plate}$

$$= 1.2 \times (10 \times 10^{-3}) \times (250 \times 10^{-3})$$

$$= \underline{3mWb.}$$

From cast steel B/H curve:

$$H_{plate} \approx 1000 A \cdot t/m$$

$$\therefore mmf_{plate} = H_{plate} l_{plate} = 1000 \times 125 \times 10^{-3}$$

$$= \underline{125 A \cdot t.}$$

Mean Path lengths

$$l_{B1} = 140 - 25 = 115mm$$

$$l_{p1} = l_{p2} = 20 - 10 = 60mm \quad (l_{poles} = 120mm)$$

$$ag_1 = ag_2 = 6mm \quad (l_{gaps} = 12mm)$$

$$l_{plate} = (140 - 25) + (2 \times 5) = 125mm.$$

Equivalent circuit:

$$B_{poles} = \frac{\Phi}{A_{poles}} = \frac{3 \times 10^{-3}}{(25 \times 10^{-3} \times 250 \times 10^{-3})} = 0.48 \text{ T} \quad (2)$$

From B/H curve for cast steel:

$$H_{poles} \approx 275 \text{ A.t/m}$$

$$\therefore \text{mmf}_{poles} = H_{poles} \times l_{poles} = 275 \times 120 \times 10^{-3} = 33 \text{ A.t}$$

$$B_{bridge} = \frac{\Phi}{A_{bridge}} = \frac{3 \times 10^{-3}}{(20 \times 10^{-3} \times 150 \times 10^{-3})} = 0.6 \text{ T}$$

From cast-steel B/H curve

$$H_{bridge} \approx 250 \text{ A.t/m}$$

$$\therefore \text{mmf}_{bridge} = H_{bridge} \times l_{bridge} = 250 \times 115 \times 10^{-3} = 28.75 \text{ A.t}$$

$$B_{gaps} \text{ assuming no fringing: } B_{gap} = \frac{\Phi}{A_{gap}} = \frac{3 \times 10^{-3}}{(25 \times 10^{-3} \times 250 \times 10^{-3})} = 0.48 \text{ T}$$

$$H_{gap} = \frac{B_{gap}}{\mu} \text{ where } \mu = \mu_0 = 4\pi \times 10^{-7} \text{ for free space}$$

$$= \frac{0.48}{(4\pi \times 10^{-7})} = 381.97 \times 10^3 \text{ A.t/m}$$

$$\text{mmf}_{gaps} = H_{gap} \times l_{gaps}$$

$$= 381.97 \times 10^3 \times 12 \times 10^{-3}$$

$$= 4583.66 \text{ A.t}$$

Ampere's Law

$$NI = \oint \vec{H} \cdot d\vec{l}$$

$$100 \times I = \text{mmf}_{bridge} + \text{mmf}_{poles} + \text{mmf}_{gaps} + \text{mmf}_{plate}$$

$$I = (28.75 + 33 + 4583.66 + 125) / 100$$

$$\approx 23.85 \text{ Amps} = 47.7 \text{ Amps}$$

Question 3. Total Marks - 20

- a) Describe and compare the direct and indirect induction methods used when performing an MPI inspection. Give an example of how these would be implemented in practice.

(8 marks)

Answer:

Magnetization Using Direct Induction (Direct Magnetization) involves passing a current directly through the component. Using the right-hand rule it is known that the magnetic lines of flux form normal to the direction of the current and form a circular field in and around the conductor.

Examples that could be described include the Head Shot Method or Prods.

Magnetization Using Indirect Induction (Indirect Magnetization) is accomplished by using a strong external magnetic field to establish a magnetic field within the component.

Examples that could be discussed include Permanent or Electro magnets, Coils or Solenoids.

- b) Discuss the importance of, and the techniques that can be used in, demagnetization of a ferromagnetic component.

(8 marks)

Answer:

After conducting a magnetic particle inspection, due to residual magnetism, it is usually necessary to demagnetize the component.

Remnant magnetic fields can:

Affect machining by causing cuttings to cling to a component.

Interfere with electronic equipment such as a compass.

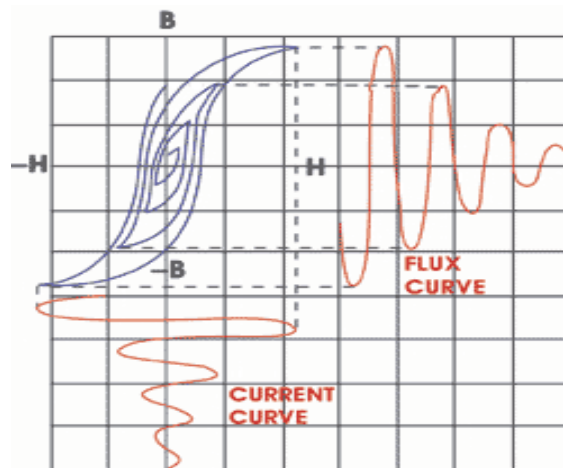
Create a condition known as "arc blow" in the welding process.

Arc blow may cause the weld arc to wander or filler metal to be repelled from the weld.

Cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Removal of a field may be accomplished in several ways. Examples include:

*Randomising the orientation of the magnetic domains can be achieved most effectively by heating the material above its curie temperature, or
subjecting the component to a reversing and decreasing magnetic field (see the figure below) will return the dipoles to a nearly random orientation throughout the material. This can be accomplished by pulling a component out and away from a coil with AC passing through it, or alternately using an electromagnetic yoke with AC selected.*



- c) A portable coil with radius 0.25m and 200 turns is to be used to magnetize a ferromagnetic part. Assuming that the coil can be treated as a simple current loop, and has a D.C. magnetizing current of 5A, determine the central flux density values with:

- i) The coil in free space, and

(2 marks)

Answer:

Using:

$$B = \frac{\mu_r \mu_o NI}{2R}$$

With $\mu_r=1$ for free space:

$$B = \frac{(4\pi \times 10^7) \times 200 \times 5}{2 \times 0.25}$$

$$B = 2.51 \times 10^{-3} T \text{ to 2 dec.places}$$

- ii) The coil around a ferromagnetic part with $\mu_r=200$.

(2 marks)

Answer:

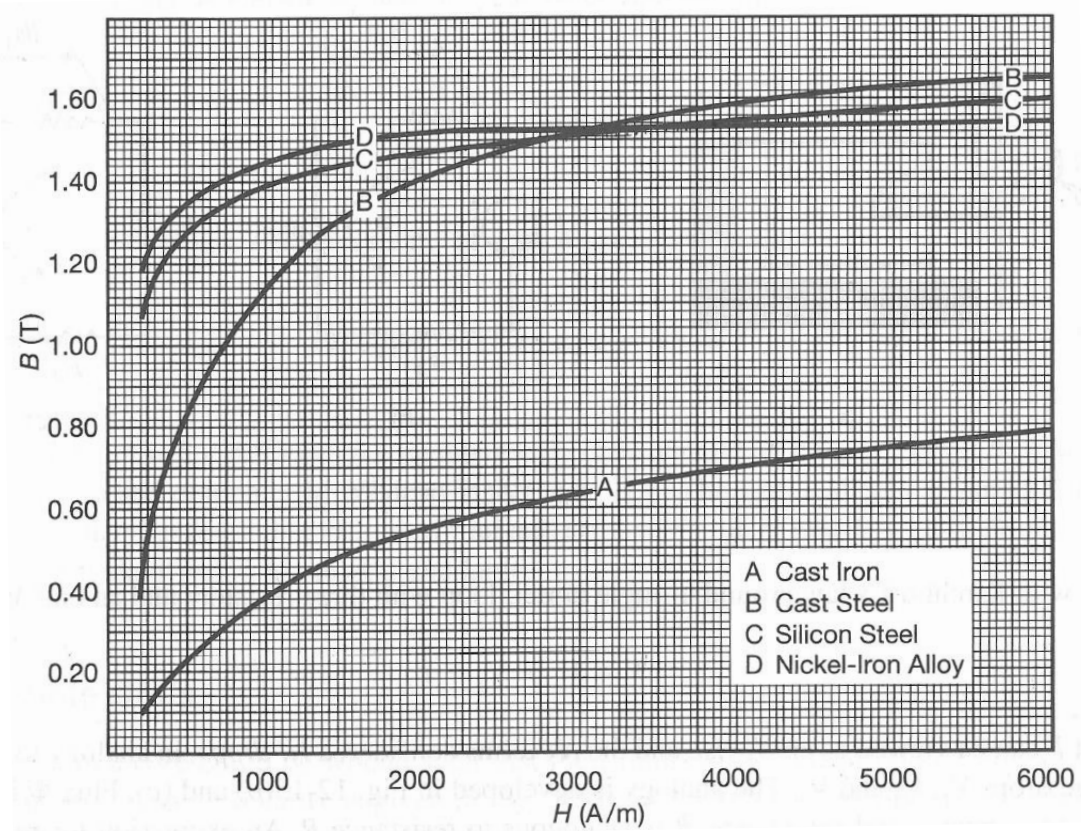
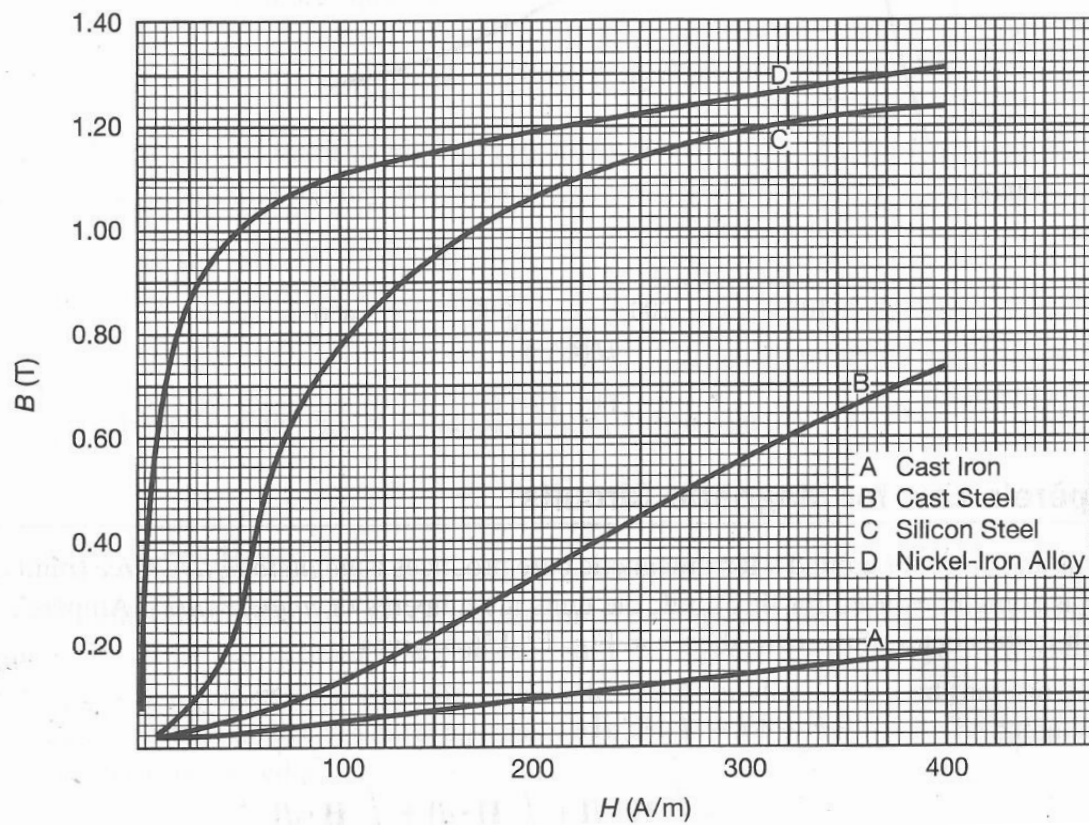
Using:

$$B = \frac{\mu_r \mu_o NI}{2R}$$

With $\mu_r=200$ for part:

$$B = \frac{200 \times (4\pi \times 10^7) \times 200 \times 5}{2 \times 0.25}$$

$$B = 0.5 T \text{ to 2 dec.places}$$



General Formula and Constants

$$\delta_{mm} = \frac{661}{\sqrt{f\mu_r\sigma}}$$

$$\theta = \frac{x}{\delta} \times 57.3$$

$$B = \mu H$$

$$\mu_r = \frac{\mu}{\mu_o}$$

$$\mu_o = 4\pi \times 10^{-7}$$

Current Loop Centre Flux Density

$$B = \frac{\mu_r \mu_o I}{2R}$$

Solenoid Centre Flux Density

$$B = \mu n I$$

$$n = \frac{N}{h}$$

Magnetic Circuit Equations

$$\mu_o \iint J \cdot \partial s = \oint \vec{B} \cdot \vec{\partial l}$$

$$V_L = -L \frac{\partial I}{\partial t} \quad V_L = -N \frac{\partial \Phi}{\partial t}$$

$$mmf = H \cdot l \quad R_m = \frac{l}{\mu A} \quad F_m = N \cdot I \quad R_m = \frac{mmf}{\Phi}$$