Magnetic characterisation of grain size and precipitate distribution by major and minor BH loop measurements

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1. Introduction

Non-destructive evaluation (NDE) of steel microstructure using electromagnetic (EM) sensors can be used for process control during fabrication or damage monitoring in-service since microstructural features, such as grain size, phase balance, precipitation etc., affect the magnetic response. The use of the magnetisation (BH) curves, and in particular their major and minor loops, for the assessment and NDE of ferritic steels has gained increasing consideration over the past decade e.g. for inspection of cold rolling \cite{1,2}, creep \cite{3} and degradation (fatigue) \cite{4} in a range of steels. Whilst there has been significant work on developing empirical relationships between major/minor loop measurements and mechanical properties, it is invariably necessary to look at the microstructures in order to interpret and make better use of these relationships. The dependence of coercivity on grain size has long been reported to be an inverse linear or an inverse square root relationship, i.e. coercivity linearly increasing with the reciprocal of grain size or the reciprocal of the square root of grain size, based on experimental data \cite{5,6} as well as theoretical calculation \cite{7,8}. Landgraf et al. \cite{6} reported generally inverse linear dependence for electrical steels and compared their results with the literature data. More interestingly, they took notice of the influence of the grain size distribution breadth, which had often been overlooked in the past, although recently modelling work has been reported for grain size distributions on low field permeability \cite{9}. It is often beneficial to be able to characterise the microstructural feature distribution, as opposed to single microstructural parameters e.g. grain size distribution rather than average grain size, to give better understanding and prediction of the microstructure-property relationship.

Major/minor magnetisation loop measurements have proved sensitive to the distribution of microstructural features such as precipitates, grain boundaries and dislocations in complex microstructures, e.g. in power plant steels \cite{10}, and have the potential of being used to look at selected microstructural features of interest, for example, through minor loop measurements at different points within a larger magnetisation cycle by applying bias fields. More often than not, it is challenging to separate the effect of one type of microstructural feature from the other. For example, grain size effect may appear insignificant on some major loop properties i.e. coercivity or remanence when there are other microstructural features within grains (such as precipitates or dislocations) or there is a significant amount of second phase, as seen in some carbon or high-alloy steels \cite{11,12}. However, even in these cases, grain boundaries are still expected to interact with the processes of domain wall (DW) movement or domain rotation. One may capture these effects by minor loop properties for a certain range of amplitudes or bias fields. In this paper, we have been able to vary and characterise grain size distributions and the precipitate distributions within the grains individually and establish a fundamental and quantitative link...

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between these two individual microstructural variables and the relevant magnetic properties by major and minor loop measurements. This fundamental study will help separate their individual effects, rather than inferred effects from complex microstructures, so as to facilitate the application of this technique to the NDE of selected microstructural features of interest.

2. Materials and experimental details

An extra low carbon (ELC) steel with 0.003 wt% C was normalised at 1000 °C, 1100 °C and 1200 °C for half an hour to obtain different grain size distributions. Three rod samples of 5 mm in diameter and 50 mm length in the different conditions, referred to as ELC–T1000, ELC–T1100 and ELC–T1200 respectively, were received from our partners (see Acknowledgement) together with the grain size data (equivalent circular diameter distributions) that had been obtained by Electron Backscatter Diffraction.

A model laboratory steel (referred to as CuLS), featuring high Cu and S content, was produced with a microstructure consisting of very coarse ferrite grains and many precipitates within the walls of the particles. Energy Dispersive X-ray Spectroscopy (EDX), equipped in FEG–SEM, were used to analyse the composition of the precipitates in the CuLS samples.

An in-house BH Analyser developed at the University of Manchester, described in [13], was used for BH loop measurement. A magnetic field was applied using a silicon-steel U-core with two excitation coils wrapped around the legs and driven by two power amplifiers fed with a low frequency time varying signal. The machined cylindrical sample was fitted into a slot in the core, to maximise coupling between core and sample. The axial applied field (H) was measured using a sensitive (0.16 mV/mAmT) Quantum Well Hall sensor, also developed at the University of Manchester. The axial flux density of the induced field (B) was measured using a 30-turn encircling coil connected to an instrumentation amplifier. A 1 Hz sinusoidal excitation was used for the measurement of the major loops and the minor loops without a bias field and 10 cycles were recorded and averaged.

3. Microstructures

3.1. Extra low carbon steel

All the ELC samples have a simple microstructure consisting of only ferrite grains. Fig. 1 shows the different grain size probability distributions. The ELC–T1000 sample exhibits the narrowest size distribution amongst the three samples with an average grain size at 19 μm and a standard deviation of 11 μm and a mode at 14 μm. As the normalising temperature increases the grain size distributions broaden significantly. As a result, the average ECD grain size and the standard deviation approximately doubled for 1100 °C and doubled again for 1200 °C. The mode of ECD, however, increase less significantly, being approximately 21 μm and 38 μm for the 1100 °C and 1200 °C

Table 2
Heat treatment conditions.

| Sample      | Heat treatment condition             |
|-------------|--------------------------------------|
| Ascast      |                                       |
| 1N5min      | Normalising at 950 °C for 5 min       |
| 3N5min      | Normalising at 950 °C for 5 min for three times |
| 3N30min     | 3N5min + normalising at 950 °C for 30 min |
| 3N3h        | 3N5min + normalising at 950 °C for 3 h |
| 3N8h        | 3N5min + normalising at 950 °C for 8 h |

Nomenclature

| B_r | Minor remanence |
| B_h | Remanence       |
| H_r | Minor coercivity|
| H_c | Coercivity      |
| l_0 | Full width at half maximum of an incremental permeability peak |
| N_p | Number density of precipitates |
| W_h | Minor hysteresis loss |
| W_p | Hysteresis loss |
| ΔH | Minor loop amplitude |
| Φ | Total area fraction of precipitates |
| φ_p | A parameter characterising the combined effects of precipitate size and interpartical spacing on coercivity |
| l_0 | Nearest neighbour spacing of precipitates |
| μ_p | Incremental permeability |
| μ_p max | Maximum incremental permeability |
| μ_p min | Low-field or near-initial permeability |
| d_c | Critical precipitate size for effective pinning to domain walls |
| d_p | Precipitate size |
| f_p pin max | Maximum pinning strength to domain walls |
| f_p pin | Pinning strength to domain walls |
| f_p pin | Average precipitate size |
| f_p pin max | Mode of precipitate size distribution |
| f_p pin | Incremental permeability peak position |
| l_0 | Average nearest neighbour spacing of precipitates |
| CDF | Cumulative distribution function |
| CuLS | Laboratory steel featuring high Cu and S content |
| DW | Domain wall |
| ECD | Equivalent circular diameter |
| EDX | Energy Dispersive X-ray Spectroscopy |
| ELC | Extra low carbon |
| EM | Electromagnetic |
| FEM–SEM | Field Emission Gun Scanning Electron Microscopy |
| MFP | Mean free path |
| NDE | Non-destructive evaluation |
| PDF | Probability density function |

Table 1
Chemical composition of the laboratory steel (wt%).

| C | Cu | S | Mn | Si | Ni | N | P | Al | Ti |
|---|----|---|----|----|----|---|---|----|----|
| 0.0023 | 0.5 | 0.034 | 0.21 | 0.011 | 0.5 | 0.001 | 0.001 | 0.002 | 0.0001 |
CuS-rich laboratory steel

Fig. 2 and Fig. 3 show the microstructures and the grain size distributions respectively for all the CuLS samples. The as-cast microstructure shows very coarse ferrite grains with a very broad size distribution (average size $\pm 162 \pm 143 \mu m$). Subsequent normalising heat treatments significantly refined the grains giving an average ECD grain size of approximately of 25–35 $\mu m$ and a much narrower size distribution than the as-cast material. The grain size distributions for all the as-normalised samples are similar. Thus, the major microstructural differences between the as-normalised CuLS samples are the precipitate sizes and distributions.

Fig. 4 shows typical precipitates present in the as-cast sample including some very coarse $(Mn,Cu)$-S particles, with Cu-rich phase co-precipitating around them, as illustrated in the element mapping shown in Fig. 5, and many fine particles. The bi-modal precipitate size distribution is qualitatively in agreement with the literature e.g. [14,15]. The fine particles show significant variability in composition, particularly the S content: some particles are relatively rich in S, Mn and Cu with different $(Mn + Cu):S$ ratio, collectively referred to as $(Mn,Cu)-S$; the other particles are either free of, or poor in, S ($<0.01 \text{ at.\%}$) and have similar EDX spectra as the matrix. These S-poor particles are, in general, slightly finer than the fine $(Mn,Cu)-S$ ones. Fig. 6 plots the atomic percentage of $(Mn + Cu)$ content as a function of that of S for a number of typical precipitates that are smaller than 0.5 $\mu m$ in ECD for all the CuLS samples, with the colour of data points mapped to the precipitate size. The number density of the particles larger than 0.5 $\mu m$ is two or three orders of magnitude lower than the finer precipitates. Their size and number do not change and hence any influence on the magnetic properties will remain constant in all the samples. Please note the S-free particles are excluded from Fig. 6 by the logarithm scale. A number of the $(Mn,Cu)-S$ precipitates are identified as $(Mn,Cu)_xS_{1-x}$ (where
Based on the fact that they occur around the (Mn + Cu):S = 0.5 trend line in Fig. 6 and also the literature [15] reporting fine (Mn,Cu)S$_2$ particles found in similar as-cast (Cu,S)-rich low carbon steels. Neither these (Mn,Cu)S$_2$ particles nor the S-free ones are detected in the as-normalised samples, which indicates they are metastable phases probably resulting from the fast kinetics of precipitation during casting. The coarse (Mn,Cu)-S particles formed in the solute-rich inter-dendritic region before final solidification and hence were able to grow very large. They are relatively stable and not expected to coarsen during the subsequent normalising heat treatments. In contrast, the fine particles, having precipitated at lower temperatures, are less stable and have coarsened during the normalising heat treatments, as can be observed in Fig. 7. The images have been intentionally selected to show the similar size of the large particles. The majority of the coarse particles (>0.5 μm) in the as-normalised samples are identified as (Mn,Cu)$_{1-x}$S or (Mn, Cu)$_x$S$_2$ (0 ≤ x ≤ 0.4) according to the dashed lines for different (Mn + Cu):S ratios in Fig. 6, which is also in good agreement with the literature [15–18]. The finer particles (<200 nm) in the as-normalised samples, however, exhibit certain variability in the (Mn + Cu):S ratio, as can be observed in Fig. 6, and...
are also collectively referred to as (Mn,Cu)-S. Note that they are all non-magnetic and hence can be treated as the same type in terms of their pinning effects to DWs.

Fig. 8 shows the precipitate size ($d_p$) and inter-particle spacing (characterised as nearest neighbour spacing, referred to as $l_{nn}$) distributions in the form of a probability density function (PDF) and a cumulative distribution function (CDF) for the as-normalised samples. It should be noted that the very coarse (Mn,Cu)-S particles are too large and few in number to be shown on these distributions. There appears to be a very slight $d_p$ broadening with insignificant change in $l_{nn}$ distribution after a five-minute normalising (1N5min). It is therefore safe to say that major microstructural change between the as-cast and 1N5min samples is in the grain size distribution, as expected of such a short normalising heat treatment. There is a broadening of both $d_p$ and $l_{nn}$ from 1N5min to 3N5min, which indicates precipitate coarsening has occurred during the initial short multiple normalising cycles. In the next stage between the 3N5min and the 3N30min, $d_p$ continues increasing whilst $l_{nn}$ remains more or less constant. This would be consistent with the fine (Mn,Cu)-S precipitates growing larger by changing their composition, in particular enrichment of Mn [15], rather than coarsening by consuming their neighbours. There is again a significant broadening of both $d_p$ and $l_{nn}$ distribution after eight hours of normalising, which indicates coarsening...
is dominating as the (Mn,Cu)-S become compositionally stable. The 3N3h appears to be in the transition between an alloying-dominating (change in composition) and a coarsening-dominating stage, as indicated by the emergence of double peaks in the ln(n) distribution, as can be seen in Fig. 8(c). These behaviours are evidenced by Fig. 9 showing the Mn:

\[ \text{Mn: (Mn + Cu) ratio probability distribution for the fine precipitates smaller than 500 nm shifting from the Cu-rich region to the Mn-rich direction for normalising up to 3N30min; and, after eight hours of normalising, settling where Cu and Mn are more balanced near the Mn-rich region probably between 0.5 and 0.9 (Fig. 9); and at the same time where the (Mn + Cu):S ratio, in general, is converging to the more stable values between 1.6 and 2, as can be observed in Fig. 6.}

The total area fraction (\(\Phi\)) and number density per unit area (\(N_a\)) for the precipitates of \(d < 0.5 \mu m\) are given in Table 3.

**Table 3**

|                | \(\Phi \times 10^{-3}\) | \(N_a \times 10^{13} \text{m}^{-2}\) |
|----------------|-------------------------|------------------------------------|
| Ascast         | 2.78 ± 1.00             | 1.55 ± 0.68                        |
| 1N5min         | 3.59 ± 1.32             | 1.48 ± 0.45                        |
| 3N5min         | 6.48 ± 3.42             | 0.83 ± 0.28                        |
| 3N30min        | 5.82 ± 5.67             | 0.74 ± 0.33                        |
| 3N3h           | 3.83 ± 0.47             | 0.76 ± 0.11                        |
| 3N8h           | 10.66 ± 1.69            | 0.73 ± 0.21                        |

is dominating as the (Mn,Cu)-S become compositionally stable. The 3N3h appears to be in the transition between an alloying-dominating (change in composition) and a coarsening-dominating stage, as indicated by the emergence of double peaks in the \(I_{1\mu m}\) distribution, as can be seen in Fig. 8(c). These behaviours are evidenced by Fig. 9 showing the Mn:

\[ \text{(Mn + Cu) ratio probability distribution for the fine precipitates smaller than 500 nm shifting from the Cu-rich region to the Mn-rich direction for normalising up to 3N30min; and, after eight hours of normalising, settling where Cu and Mn are more balanced near the Mn-rich region probably between 0.5 and 0.9 (Fig. 9); and at the same time where the (Mn + Cu):S ratio, in general, is converging to the more stable values between 1.6 and 2, as can be observed in Fig. 6.}

The total area fraction (\(\Phi\)) and number density per unit area (\(N_a\)) for the precipitates of \(d < 0.5 \mu m\) are given in Table 3.

**4. Major and minor loop properties and their links to microstructures**

**4.1. Major loop properties and linkage to microstructural parameters**

**4.1.1. Extra low carbon steels**

Fig. 10 (a) shows the major loops for the ELC steel samples. It should be noted that the samples were magnetised to near technical saturation by applying a field of approximately 35 kA/m whilst only the [-5kA/m, 5kA/m] region is shown in Fig. 10 (a). The properties extracted from the major loops including coercivity, \(H_c\), remanence, \(B_r\), and hysteresis loss (the area encircled by a major loop), \(W_h\), are given in Table 4.

\[ H_c \text{ values decrease with the average or mode of grain size by a power law with an exponent at approximately 0.5 or 0.15 respectively and a negative pre-exponent constant for the ELC steels, as shown in Fig. 10 (b), which is qualitatively in agreement with the literature}[5,6]\ reporting \(H_c\) decreasing with average grain size also by a power law but with a different exponent at \(\sim 1\) or \(\sim 0.5\) and a positive pre-exponent constant. These empirical relationships as well as some theoretical predictions \[8,7\] are by no means universal. For example, Goodenough’s \[8\] \(d^{1/2}\) model fails for \(d < 50 \mu m\), where \(d\) is average grain diameter; Landgraf’s \[6\] \(d^{1/2}\) dependence, although valid for a broader range \((10 < d < 120 \mu m)\) that covers the grain size range in this paper, was obtained using electrical steels with intra-grain precipitates present in all the samples and unavoidable texture in some of the samples. \(H_c\) is the applied field strength under which irreversible domain processes most frequently occur. Thus, it is fundamentally more logical to correlate \(H_c\) with the mode than the average of grain size.

\[ W_h \text{, however, representing a cumulative result of all the irreversible domain processes over a major loop cycle, is collectively affected by all the grains and therefore should be correlated with the average grain size. The } W_h \text{ values for the ELC samples decrease with the average grain size by a power law at an exponent of } \sim 1.57 \text{ as shown in Fig. 10 (c). The } B_r \text{ values are hardly distinguishable between the samples considering the scatter as can be seen in Fig. 10 (c) and Table 4.}

![Fig. 10. (a) Major loops; (b) \(H_c\) and (c) \(W_h\) and \(B_r\) as a function of the grain size, for the extra low carbon steel samples. \(W_h\) and \(B_r\) are plotted against average grain size.](image-url)
associated with a DW pinning event, more of a macroscopic descriptor of domain pinning effects. These complex effects cannot be explicitly captured by the major loop properties but may be characterised by minor loop measurements, which will be discussed later.

Non-magnetic intra-grain precipitates influence coercivity by pinning DWs due to DWs’ strong tendency to stick to a precipitate to reduce the wall energy after Kersten [19] or due to the internal magnetic poles in a precipitate redistributing themselves when being passed by a DW to minimise magnetostatic energy after Neel [20]. Strongest pinning occurs where the precipitate size $d_p$ is comparable with the DW thickness, which was reported to be around 120 nm in ferrite phase in carbon steels [21]. The number density of precipitates, $N_p$, also affects the pinning as a DW can be pinned by more than one precipitate at the same time. Combining both effects yields $H_I \propto \sigma_p = N_p^{1/3} d_p^2$ following Kersten’s model [19] or an empirical relationship reported in [22]. Fig. 12 shows a general trend of $H_I$ and $B_I$, initially increasing with coarsening of precipitates and then decreasing after a critical point around $\sigma_p \approx 3.5$ nm between 3N3h and 3N8h. The decrease of the $H_I$ may be attributed to the fact that a significant number of precipitates has reached a critical size $\approx 120$ nm i.e. comparable with the DW thickness, and hence their pinning effects start weakening with further coarsening. The initial increase of $B_I$ is expected from the coarsening of precipitates reducing the number density of magnetic free poles and hence their contribution to demagnetisation; the latter decrease may be attributed to the fact that some of the precipitates have grown large enough (i.e. approximately $\approx$ 200 nm [8], as seen in Fig. 8 for the 3N8h sample) for closure domains to form around them, which promotes demagnetisation and hence decreases $B_I$.

It has been shown that major loop properties are sensitive to an average or a total value of microstructural parameters, as opposed to a distribution, as a result of cumulative effects of all microstructural features. There may be an indication of microstructural feature distribution in the shape of a major loop, particularly near its shoulder or knee (Fig. 11). For example, a broad distribution of a high density of

Table 4
Magnetic properties measured from the major and minor loops.

| Sample       | $H_I$ (A/m) | $B_I$ (T) | $W_b$ (J/m$^3$) | $\mu_{\text{Anis}}$ | $B_{\text{p}}$ (A/m) | $\mu_{\text{ni}}$ | $H_{\text{Jpin}}$ (A/m) |
|--------------|-------------|-----------|-----------------|---------------------|----------------------|------------------|----------------------|
| ELC-T1000    | 850 ± 14    | 0.871 ± 0.032 | 6624 ± 203     | 1210 ± 54           | 475 ± 39             | 433 ± 17        | 1786 ± 106           |
| ELC-T1100    | 796 ± 10    | 0.899 ± 0.017 | 6181 ± 118     | 1475 ± 31           | 330 ± 19             | 514 ± 22        | 1378 ± 43            |
| ELC-T1200    | 711 ± 3.5   | 0.874 ± 0.004 | 6015 ± 44      | 1781 ± 77           | 220 ± 10             | 595 ± 13        | 1081 ± 65            |
| As cast      | 657 ± 22    | 0.813 ± 0.034 | 5690 ± 226     | 1897 ± 49           | 192 ± 2              | 690 ± 24        | 1161 ± 34            |
| 1N5min       | 643 ± 5.4   | 0.808 ± 0.011 | 5501 ± 85      | 1670 ± 31           | 257 ± 20             | 552 ± 4         | 1241 ± 29            |
| 3N5min       | 638 ± 26    | 0.824 ± 0.010 | 5418 ± 179     | 1516 ± 28           | 266 ± 14             | 467 ± 15        | 1395 ± 54            |
| 3N30min      | 675 ± 16    | 0.853 ± 0.029 | 5693 ± 119     | 1487 ± 26           | 313 ± 15             | 435 ± 16        | 1473 ± 37            |
| 3N3h         | 690 ± 26    | 0.891 ± 0.027 | 5750 ± 185     | 1674 ± 27           | 321 ± 18             | 467 ± 20        | 1292 ± 27            |
| 3N8h         | 683 ± 8.8   | 0.846 ± 0.010 | 5626 ± 50      | 1587 ± 40           | 317 ± 7              | 478 ± 15        | 1398 ± 42            |
dislocations within grains results in a rounded shoulder whilst recovery by annealing narrows the distribution of DW-pinning features and increases the major loop squareness \([23]\). However, such shape changes cannot be easily and quantitatively characterised. Besides, when there is more than one type of microstructural feature present, their effects on the major loop properties cannot be separated.

4.2. Minor loop properties and linkage to microstructural feature distributions

Fig. 13 shows a typical series of minor loops with increasing amplitudes. The inset illustrates the definition of a set of minor loop properties including incremental permeability \(\mu_s\), minor coercivity \(H_{c,m}\), minor remanence \(B_{r,m}\) and minor hysteresis loss \(W_{h,m}\), defined by analogy with their major loop counterpart to characterise the minor loop behaviours.

4.2.1. Extra low carbon steels

Fig. 14 shows the minor loop properties as a function of the minor loop amplitude for all the ELC samples. The \(\mu_s\) profiles feature a single peak that can be characterised by its peak value, \(\mu_{max}\), peak position, \(H_{p}\), and the peak width at the half maximum, \(H_{fwhm}\), and they all fit well with a multi-term Gaussian function, as can be seen in Fig. 14 (a). The peaks occur approximately where the minor loops transit from a lenticular shape to a sigmoid shape typical of a major loop. Similar behaviours were previously reported on other ferromagnetic steels e.g. power plant P9 and T22 steels in different heat treated conditions \([10]\). The \(\mu_s\) value at 35 A/m, approximately one thousandth of the major loop amplitude, was taken to characterise the low-field or near-initial permeability, referred to as \(\mu_{ni}\), as illustrated in Fig. 14 (a). The values of these characteristic parameters are given in Table 4. Fig. 15 shows these magnetic parameters as a function of corresponding microstructural parameters that characterise grain size distributions.

Fig. 13. A series of minor loops with different amplitudes.

Fig. 14. Minor loop properties as a function of the minor loop amplitude for the extra low carbon steels. (a) \(\mu_s\), (b) \(H_{c,m}\), (c) \(B_{r,m}\) and (d) \(W_{h,m}\). The solid lines are fitting lines with multi-term Gaussian relationships in (a), power law and exponential relationships for low-amplitude portion and remainder of the curves respectively in (b), (c) and (d).
Both $\mu_2$ and $\mu_{\text{max}}$ monotonically increase with average grain size. The latter shows a higher sensitivity than the former as can be observed in Fig. 15 (a). At very small amplitudes such as the one for $\mu_2$, pre-dominant domain processes are 180° DWs oscillating between two equilibrium positions under the applied field of $-\Delta H/2$ and $\Delta H/2$ respectively. The oscillation can be translational motion or bending back and forth if the DW is treated as being rigid or flexible respectively. In either model, $\mu_2$ is influenced by the mean free path (MFP) to DW motion, which is determined by the average grain diameters of all grains. As $\Delta H$ increases there will be increased coordination in the domain movement behaviours between some adjacent grains owing to the increased influence of the applied field, which effectively weakens the effect of the grain boundary as if these domains passed through the grain boundaries whose $f_{\text{pin}} < \Delta H/2$. These passed grain boundaries during minor loop cycles are not affecting $\mu_2$ any more. That is, $\mu_2$ is only sensitive to the grain boundaries that are effectively pinning DWs. Since $f_{\text{pin}}$ is inversely proportional to grain size $[8,7]$ those larger than a critical size, determined by the corresponding $f_{\text{pin}}$, are therefore separated out. It follows that $\mu_2$ is effectively sensitive to a truncated grain size distribution; an amplitude sweep is equivalent to truncating a grain size distribution from right to left (see Fig. 1 (a)). Note the probability density of a truncated distribution is scaled up. This accounts for a higher sensitivity of $\mu_{\text{max}}$ than $\mu_2$ to average grain size. $R_\Delta$ and $H_{\text{hyst}}$ decrease with the mode and standard deviation of the grain size distributions respectively as shown in Fig. 15 (b) and (c).

These behaviours and their consistency manifest a strong link between microstructural feature distributions (i.e. grain size distribution in this case) and incremental permeability profiles. The fundamental reason is that the latter can be mapped to the $f_{\text{pin}}$ distribution, which has been explained in detail in our previous paper [10]. In short, the broader a grain size distribution the narrower its associated $\mu_2$ profiles (please note that the breadth of a $\mu_2$ profile is quantitatively characterised by its $H_{\text{hyst}}$ value in this paper). Thus, one can characterise grain size distribution using $\mu_2$ profiles by minor loop measurements.

Although the truncated portions of the grain size distribution are separated out in $\mu_2$, they are still actively affecting irreversible domain processes during a minor loop cycle and hence collectively effect the minor loop shape and other minor loop properties including $H^\text{m}$, $B^m$ and $W^m$. Therefore, if these grains are of interest instead they can be characterised by these minor loop properties. For conciseness in describing their profiles, we divide the amplitude range roughly into three regions in terms of corresponding $\mu_2$ values. The region in which $\mu_2 \geq H_{\text{hyst}}/2$ is referred to as medium amplitudes; the region to the left and the right respectively is referred to as low and high amplitudes. In general, the trend of $H^m$, $B^m$ and $W^m$ changing with grain size inverses over the medium amplitudes. That is, at low amplitudes they all increase with grain size, whilst at high amplitudes they all exhibit a similar trend to their major loop counterparts. The low-amplitude portion fits well with a power law relationship, i.e. $y = a_1x^{a_2} + a_3$ whilst the remaining curves fit well with a bi-exponential relationship i.e. $y = c_1 \exp(c_2x) + c_3 \exp(c_4x)$, where $a_1$, $a_2$, $a_3$ and $c_1$, $c_2$, $c_3$, $c_4$ are all constants independent of minor loop amplitude, as shown in Fig. 14 (b)–(d). The values of the constants for $H^m$ are given in Table 5. All these constants show either a similar or inverse trend to the grain size distribution parameters. Similar to the $f_{\text{pin}}$ distribution being mapped to $\mu_2$ profiles its cumulative distribution can be mapped to other minor property profiles since these properties reflect a cumulative result of the irreversible domain processes during a minor loop cycle. It follows that one can characterise the cumulative microstructural feature distribution using the $H^m$, $B^m$ and $W^m$ profiles. Instead of truncating the PDF of a grain size distribution, these properties are actually sampling grains by swiping the CDF from right to left. This explains why the low-amplitude values of these properties increase with average grain size because more grains in the broader distributions are sampled as can be observed in Fig. 1 (b). As the amplitude increases more grains are sampled at a rate similar to the tangent slope of the cumulative

| $a_1$ | $a_2$ | $a_3$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ |
|------|------|------|------|------|------|------|
| 0.01836 | 1.568 | 2.052 | 2.3398E+02 | 1.1716E-04 | −2.2759E+02 | −2.1783E-03 |
| 0.01884 | 1.1699 | −9.4861 | 2.0190E+02 | 1.1815E-04 | −1.8120E+02 | −2.3694E-03 |
| 11.47 | 0.4628 | −49.85 | 1.5596E+02 | 1.0419E-04 | −1.4546E+02 | −3.0914E-03 |
| 2.211 | 0.6964 | −11.73 | 1.3600E+02 | 1.0553E-04 | −1.6549E+02 | −2.7227E-03 |
| 0.2041 | 1.1738 | −2.5489 | 1.4656E+02 | 1.1111E-04 | −1.2603E+02 | −2.7608E-03 |
| 0.0303 | 1.5518 | 2.052 | 2.3398E+02 | 1.1716E-04 | −2.2759E+02 | −2.1783E-03 |
| 0.0240 | 1.5758 | 3.1485 | 1.6613E+02 | 1.0419E-04 | −1.4546E+02 | −3.0914E-03 |
| 0.0376 | 1.4818 | 2.2819 | 1.7039E+02 | 1.1310E-04 | −1.6799E+02 | −3.1672E-03 |
| 0.0623 | 1.3840 | 1.2923 | 1.7498E+02 | 1.0553E-04 | −1.6549E+02 | −2.7227E-03 |
distribution profiles. That is, the broader the grain size distribution, the higher values these properties start with (at low amplitudes), and the lower the rates of increase with amplitudes. Eventually, the trend inverses.

4.2.2. CuS–rich laboratory steel

Fig. 16 shows the minor loop properties as a function of amplitudes for all the CuLS samples. Similarly, their $\mu_\text{max}$ profiles feature a single peak and $H_f$ exhibit different behaviours between the low- and the high-amplitude region. The as-cast sample stands out with consistently greater $\mu_\text{max}$ values than the 1N5min sample for most of the amplitudes, the greatest $\mu_\text{max}$ and the smallest $H_f$ and $H_{bolm}$ (see Table 4), or in other words, the narrowest $\mu_\text{max}$ profile, amongst all the CuLS samples. There is continuous broadening of $\mu_\text{max}$ profiles for the as-normalised samples for normalising up to 30 min, indicated by a decreasing $\mu_\text{max}$ and an increasing $H_f$ and $H_{bolm}$. Major changes occur over the low and medium amplitudes whilst the high-amplitude $\mu_\text{max}$ remain more or less constant in the stage between 1N5min and 3N30min. There is then a significant increase in $\mu_\text{max}$ accompanied by a decrease in $H_{bolm}$, or a narrowing of $\mu_\text{max}$ profiles, in 3N3h, but then again a broadening in 3N8h, with major changes occurring over the medium-high amplitudes in the next stage between 3N30min and 3N8h. However, $H_f$ remains more or less constant in this stage.

Fig. 17 shows the $\mu_\text{ni}$ and the $\mu_\text{max}$ values as a function of precipitate distribution parameters (a) mode of $d_p$ and (b) average $d_p$ for all the CuLS samples.

![Fig. 16. Minor loop properties as a function of the minor loop amplitude for the CuS-rich laboratory steel. (a) $\mu_\text{ni}$; (b) $H_f$.](image)

![Fig. 17. Minor loop properties $\mu_\text{ni}$ and $\mu_\text{max}$ as a function of precipitate distribution parameters (a) mode of $d_p$ and (b) average $d_p$ for all the CuLS samples.](image)
until it reaches the maximum value that is normalised to unity by the exponential function when \( d_p = d_c \), and then decreases when \( d_p > d_c \). The pre-exponent constant \( A \) is to condition the \( f_{pin} \) values to distribute, overall, as broadly as possible between 0 and 1, for all the samples and different \( d_c \) values, which has been roughly determined to be in the range between 300 and 400, by trial and error. The trends for the peak positions and heights do not change with \( A \) in this range.

2. Map the relative \( f_{pin} \) distributions for different \( d_c \) values including a reported DW thickness for pure iron (38 nm) [25], the \( \bar{d}_p \) and \( d_p \) value, where minimum \( \mu_n \) and \( \mu_{max} \) occur and a reported critical size (120 nm), for non-magnetic spherical cementite precipitates within ferrite grains in carbon steels, where maximum coercive force occurs [21].

3. Compare the trends for \( f_{pin} \) peak positions as a function of \( \bar{R}_H \). As explained in our previous work [10] \( f_{pin} \) peak positions should be proportional to \( \bar{R}_H \) and will be referred to as relative \( \bar{R}_H \). However, \( \mu_{max} \) is affected by not only \( f_{pin} \) peak height (affecting how many DWs are moving) but also the interaction range (affecting how much the DWs move). The latter is influenced by inter-particle spacing distribution and grain size [10,26].

4. Assume \( \mu_{max} \propto f_{pin_{max}} l_{nn} \) as a first approximation, where \( f_{pin_{max}} \) is the \( f_{pin} \) peak height and \( l_{nn} \) is the average value of \( l_{nn} \) and the term on the right is referred to as relative \( \mu_{max} \). Compare the trends for relative \( \mu_{max} \) as a function of \( \mu_{max} \).

5. Re-sample the precipitates with \( d_p \geq d_0 \), where \( d_0 \) increases by 5 nm increments starting from 0, and update \( l_{nn} \).

6. Repeat steps 1 to 5 until the trends are lost, which occurred at \( d_0 = 35 \) nm. Thus, the previous \( d_0, 30 \) nm, is regarded as the critical value for effective pinning the domain walls in these steels, which falls in the range (5–100 nm) for \( d_0 \) for iron reported in the literature [27].

Fig. 18 shows the relative \( f_{pin} \) distribution for different \( d_c \) values for \( d_0 = 30 \) nm. Fig. 19 shows relative \( \bar{R}_H \) and relative \( \mu_{max} \) as a function of \( \bar{R}_H \) and \( \mu_{max} \), respectively for the different \( d_c \) values. \( d_c = 105 \) nm yields best prediction to the expected trend as illustrated by the fitting line in Fig. 19. Note the value is comparable with the value (120 nm) for non-magnetic precipitates in carbon steels [21] and consistent with the \( \mu_{ni} \)

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**Fig. 18.** Relative \( f_{pin} \) distribution for different critical precipitate size (\( d_c \)) for effective pinning to DWs. (a) 38 nm, (b) 55 nm, (c) 105 nm and (d) 120 nm.

**Fig. 19.** (a) Relative \( \bar{R}_H \) and (b) relative \( \mu_{max} \) as a function of \( \bar{R}_H \) and \( \mu_{max} \), respectively. The dashed line shows a linear least-square fitting for the critical precipitate size \( d_c = 105 \) nm.
nucleation reactor pressure vessel steels. The present work sheds light on the underlying mechanism of this approach — the microstructural feature distribution governing the $f_{\text{pin}}$ distribution and the interaction range after irreversible domain processes. Fundamental studies from first principles may be needed to fully understand the physical meaning of these coefficients.

5. Discussion on interaction between grain size effects and the precipitate effects

There is approximately 20% and 11% difference in $\mu_{\text{pin}}$ and $\mu_{\text{max}}$ respectively between the as-cast and the 1N5min sample corresponding to a very slight $d_p$ broadening but significant grain refinement. There is up to almost the same percentage of change in these magnetic properties between as-normalised CuLS samples corresponding to much more significant changes in precipitate distribution with similar grain size distribution. Thus, the significant difference in the $\mu_c$ profiles between the as-cast and the 1N5min sample (Fig. 16 (a)) should be principally attributed to grain size distribution (Fig. 3) effects. We have shown that grain size has strong influences on the $\mu_c$ profile when there are no precipitates or any other significant microstructural features within the grains as in the ELC samples. We shall then discuss what roles different grain size distributions play when there are similar distributions of precipitates present; and what roles the similar distributions of precipitates play when they are in grains of different size distributions.

Consider a 180° DW being pinned by precipitates in a grain. The origin of $f_{\text{pin}}$ is twofold. First, the DW has to overcome the local potential wells associated with the precipitates. Second, DWs are subject to potential wells due to the magnetostatic energy associated with all the other grains of different orientations with the neighbouring grains having strongest influence. The smaller the grain size, the more grains with different orientations in a given volume there are and hence the deeper potential wells (higher $f_{\text{pin}}$) are to be overcome. It follows that grain size distribution can alter the $f_{\text{pin}}$ distribution associated with the precipitates within grains. In contrast the other precipitates that are not pinning the DW are not expected to contribute much to the magnetostatic energy and hence the $f_{\text{pin}}$ considering their small volume fraction. The shape of the $f_{\text{pin}}$ distribution is dependent on the number density of local potential wells associated with precipitates, i.e. the number density of precipitates, and the number density of the potential wells associated with the grains. The typical 180° DW spacing for the CuLS samples, measured from the Bitter domain patterns without an applied field, as shown in Fig. 21, using the method described in [28], is in the order of several microns. It is worth noting that the Bitter pattern is on a 2D surface whilst the spacing in the 3D bulk may be different. However, it is still safe to say that the number density of DWs is estimated to be about three or four orders of magnitude lower than the number density of precipitates. In this case, the shape of the $f_{\text{pin}}$ distribution will be

![Fig. 20. $H_{cm}$ profile fitting constant as a function of the mode of $d_p$.](image)

![Fig. 21. Static domain patterns by Bitter method without an applied magnetic field for the (a) as-cast and (b) 1N5min CuLS steel samples. Examples of domain walls, shown as the dark line features, are marked and typical 180° domain wall spacings are measured.](image)
dictated by the precipitate distribution whilst the predominant role of grain size distribution is to shift and scale the precipitate \( f_{\text{pin}} \) distribution. Therefore, narrower \( \mu_s \) profile and smaller \( d_0 \) of the as-cast sample than the 1N5smn sample can be attributed to a larger and broader grain size distribution (and hence narrower associated \( f_{\text{pin}} \) distribution) of the as-cast sample shifting the \( f_{\text{pin}} \) distribution associated with precipitates to the left and at the same time making it narrower. In the meantime, the interaction range or the MFP to DW motion may be determined by grain size considering many precipitates may be too small to effectively pin DWs making the effective inter-particle spacing greater than the width of potential wells associated with grains. In this case or at high amplitudes, the MFP is grain size limited.

In the case of a very low number density of precipitates in a smaller and narrower grain size distribution (and hence higher number density of associated potential wells and broader \( f_{\text{pin}} \) distribution), the shape of the \( f_{\text{pin}} \) distribution may be dictated by the grain size distribution, whilst the precipitates are expected to play an insignificant role. The very coarse (Mn,Cu)-S particles have a very low number density and hence are expected to play an insignificant role in the shape of \( f_{\text{pin}} \) distribution.

6. Conclusion

Major loop properties including coercivity, \( H_c \), and the hysteresis loss, \( W_h \), are sensitive to grain size when there are no precipitates within the grains but become more or less insensitive to grain size when there are a significant number of precipitates within the grains. \( H_c \) and the remanance, \( B_r \), show some sensitivity to average precipitate size and number density. Characteristic magnetic properties/parameters extracted from minor loops of a series of amplitudes including low field permeability, \( \mu_{\text{pin}} \), maximum incremental permeability, \( \mu_{\text{max}} \), and the amplitude where \( \mu_{\text{max}} \) occurs, \( H_{\text{D}} \), have proved sensitive to the grain size and precipitate distributions in the studied steels. The results indicate that there is a critical precipitate size, \( d_0 \), for effective pinning to domain walls that increases with the minor loop amplitude and there is another critical precipitate size, \( d_n \), where the precipitates are most effectively pinning domain walls. \( d_0 \) and \( d_n \) were found to be approximately 30 nm and 105 nm respectively for the studied Cu-rich extra-low-carbon laboratory steels. The minor coercivity, minor remanence and minor hysteresis loss increase with the field amplitude by a power law at low amplitudes and a bi-exponential relationship at medium and high amplitudes. Some fitting coefficients exhibit strong links to grain size or precipitate size distribution parameters. It has been demonstrated that incremental permeability profiles and the fitting coefficients for the other minor property profiles can be used to indicate grain size and precipitate distributions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.jmmm.2019.02.088.

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