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Evaluating the Suitability of Partial Recrystallisation as a Strengthening Method for Thin Gauge, High strength Non-Orientated Electrical Steel

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The increasing need for electric/hybrid electric vehicles to compete with fossil fuel powered cars has led to new requirements and designs of the electric motor. Non-Grain Oriented Steel (NOES) are primarily used within the electric motor to form both stator and rotor sections (dependant on design) and have traditionally been developed to possess excellent isotropic magnetic properties with little or no consideration for strength. The drive towards more powerful or efficient electric motors has resulted in higher rotational speeds and increasing associated requirements for high strength NOES. This study looks at utilising the well know theory of partial recrystallisation as a strengthening mechanism to determine if the strengthening effects and associated magnetic properties are acceptable for use within the rotor section. It was found that partial recrystallisation can be utilised to tailor the microstructure of NOES to create higher strength NOES that withstands operating conditions and compares favourably to commercially available high strength NOES grades; making it a viable option.

A. Introduction

NOES are fully ferritic steels with between 2 and 3.2 wt. % Si. The chemistry of NOES and their processing routes are designed entirely to optimise desirable magnetic properties such as low loss, high permeability, low coercivity and a high peak magnetization. Pampa Ghosh *et. al* stated the two most important magnetic properties for NOES were core Loss and Permeability [1]. Within an electric motor used for power generation in electric or hybrid electrical vehicles, NOES are mainly used within the stator and rotor components where the magnetization vector changes direction with time. Therefore, traditionally NOES have been developed and manufactured with the aim of improving its isotropic magnetic properties. The relationship between substrate metallurgy and magnetic properties has received extensive previous attention in the literature and comprehensive reviews can be found here [1][2][3].Electric vehicles face significant challenges when competing against petrol or diesel vehicles, one of which is range. This can partly be addressed by increasing the electric motor efficiency[1]. The efficiency of the electric motor can be increased by increasing the rotational speed and therefore the torque of the motor as highlighted in the study carried out by M. Tietz *et. al* [4]. An increase in rotational speed increases the centripetal force exerted on the rotor section of the motor meaning material strength is of increased importance. A factor that until recently has not been a driver for NOES alloy design.

Strengthening mechanisms of steel revolve around the prevention of dislocation movement and this in turn is harmful to magnetic properties due to domain wall pinning. A detailed description of the behaviour of ferromagnetic domains can be found in [5]. It is important to reduce the number of pinning sites within the material to maximise magnetic properties. This can be achieved by surface modification and removing as many microstructural heterogeneities as possible including: phase boundaries, grain boundaries, inclusions and precipitates.

A previous study was carried out by Marco A. da Cunha that observed the magnetic dependency of 3wt. % Si NOES on annealing temperatures ranging between 540ºC and 980ºC. The study stated recovery occurred between 540ºC and 660ºC, recrystallisation began at 660ºC and finished at 820ºC. Further improvements of magnetic properties post 820ºC were due to grain growth and further development of GOSS texture [6].

The driving force for recrystallisation is determined by time at temperature and cold rolling reduction. Given the narrow variation in cold reduction for industrially produced material (typically 70%), annealing temperature and time control the kinetics of the process for all practical purposes. As such these were the main process variables under consideration in the current work.

B. Experimental Procedure

For this study, 0.2mm thick 3.2wt. % Si NOES material studied was industrially processed to the point of pre-final annealing at Cogent Power's NOES production facility in Surahammer.

A review of NOES production route is provided elsewhere [7]. The received material had undergone decarburization, 2 stages of thickness reduction with an inter-anneal and is designated as pre-final anneal material (PFA).

The PFA material was stamped into Epstein sized samples with standard dimensions of 305 x 30mm and cleaned of any residual oil using ethanol, ready for laboratory annealing.

The two grades under study were designated T1 and T2, where the T1 grade had undergone a certain amount of recrystallisation and the T2 grade was the final grade laboratory simulated grade of identical composition and process history and used for comparison with the production recrystallized grade. Phase changes were not expected during annealing at T1 and T2 because of the ferrite stabilising chemical composition of the PFA grade. Due to intellectual sensitivity, the recrystallisation temperature employed for T1 and T2 cannot be disclosed.

1. *Final annealing simulations*

Final annealing simulations were carried out using a furnace under atmospheric conditions. The major difference between samples heated under atmospheric conditions and HNx atmosphere was the incomplete formation of the gamma fibre under atmospheric conditions. Therefore, it was concluded that results obtained during this study would show representative trends and would represent worst-case baseline results from magnetic properties.

Samples were heated at 26°C/s, soaked for 120s and cooled at 21°C/s using forced air with a flow rate of 3507m^3/hr.

2. *Stability Testing*

To assess the stability of the partial recrystallisation as a strengthening mechanism in service, the T1 grade underwent stability testing. Conditions for this test were predetermined by operational conditions of the electric motors. Epstein sized samples of T1 were heated to 150°C and soaked for 1 week within an atmospheric furnace, followed by magnetic and mechanical characterization.

3. Microscopy

Microstructural analysis was carried out using a Zeiss Axia Observer ZIM using AxioVision software. A minimum of 200 grains were analysed per sample. Both mechanical and chemical preparation methods were used for microscopy and texture measurements. Samples were polished to 1 micron using standard metallographic preparation methods. Sections were prepared on the L-T face of the material.

4. Magnetic characterization

Magnetic testing was carried out at the Wolfson Centre, Cardiff University using an in house single strip Epstein tester. Testing was carried out using 1.0 Tesla, 400Hz. The four magnetic properties of interest throughout this study were: magnetic core loss; permeability; coercivity and peak magnetization. Due to intellectual sensitivity, the magnetic properties presented have been normalized.

5. Mechanical characterization

Tensile testing at room temperature was carried out in accordance with ISO 6892-1:2009. Due to commercial sensitivity, the mechanical properties presented have been normalized.

C. Results

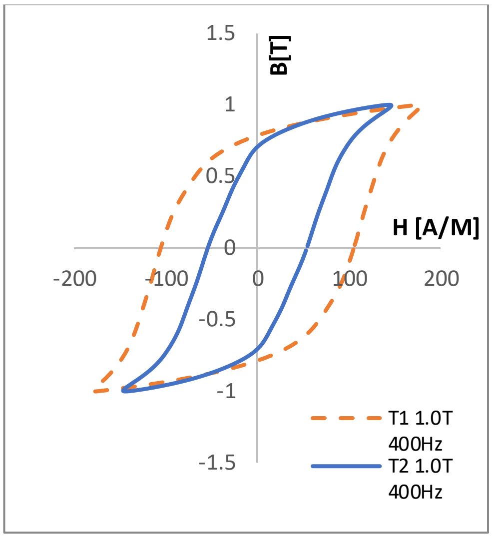

Figure 1 - Comparison of T1 and T2 B-H loops tested at 1.0T, 400Hz

Figure 1 compares the associated B-H hysteresis loops of grades T1 and T2. It shows grade T2 having a lower coercivity, lower remanence and hence a lower core loss than T1, though the permeabilities of the two grades were approximately comparable a shown in Figure 2.

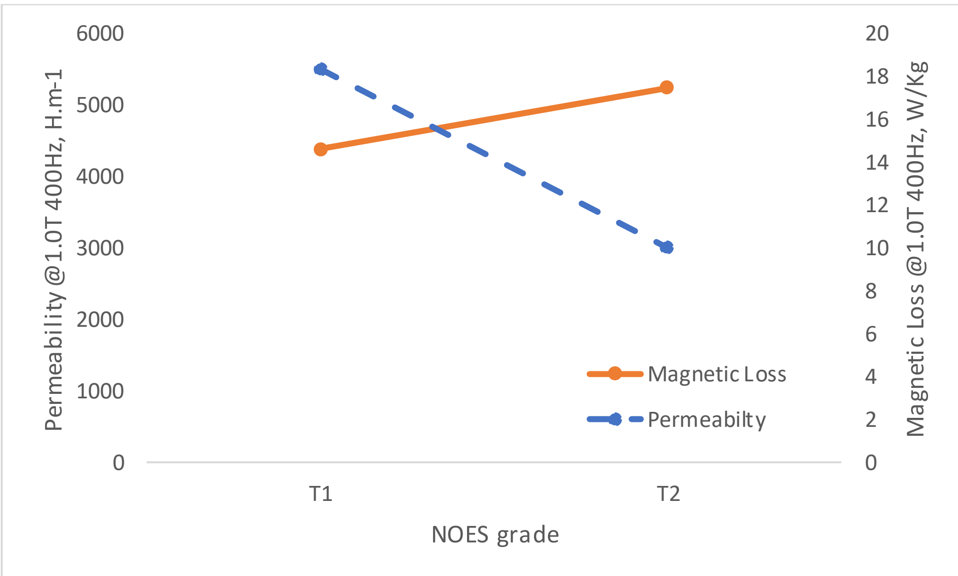

Figure 2 - Average Magnetic Loss and Average Permeability comparison between T1 and T2

Figure 3 compares the normalized yield strength and normalized strain at failure for both T1 and T2. T1 has a higher yield strength and greater ductility than T2.

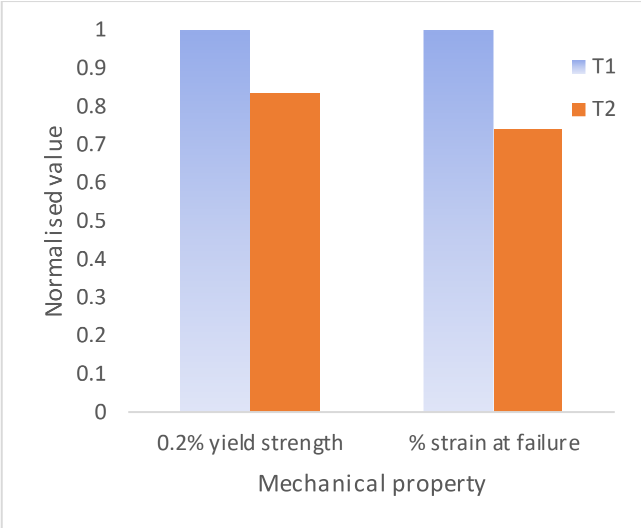

Figure 3 - Normalized yield strength and strain at failure for T1 and T2

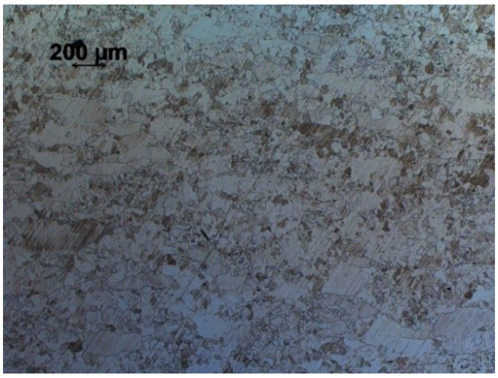

Figure 4 - Microstructure of T1

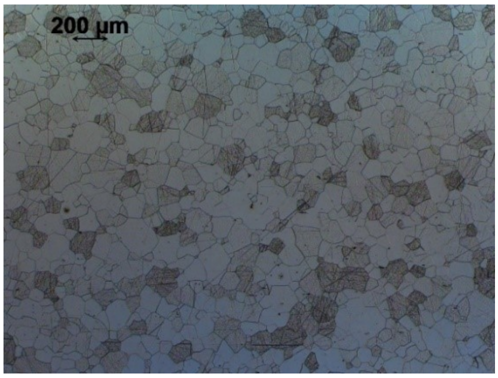

Figure 5 - Microstructure of T2

Figure 4 and Figure 5 compares the microstructure of T1 and T2. The partial recrystallized microstructure of T1 is evident in comparison to the fully recrystallized microstructure of T2. The microstructure of T1 consists of recrystallized grains surrounded by small, near equiaxed partially recrystallized grains that have yet to undergo grain growth. T2 shows a fully recrystallized microstructure with equiaxed grains and an average grain size of 108 microns showing it has undergone grain growth. This process reduces internal stress within the microstructure and produces a larger equiaxed grain structure that culminated in producing the preferable B-H loop presented in Figure 1. This was in line with the work presented in [6].

Partial recrystallisation has been determined to be a valid strengthening mechanism directly after manufacture, however the nature of recovery, recrystallisation and grain growth suggests that any additional energy supplied to the system could continue the recrystallisation process and therefore reduce its strengthening benefits. Therefore, stability testing was carried out.

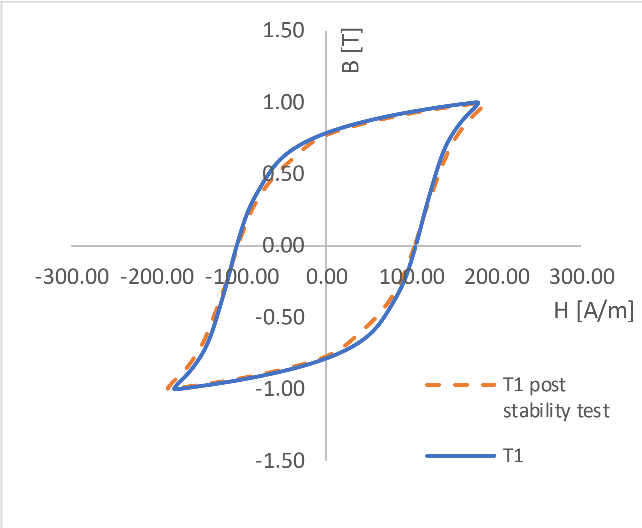

Figure 6 - B-H loop comparison between T1 and T1 post stability testing

Figure 6 highlights the differences in the associated B-H loops of T1 and T1 post stability testing. There are negligible differences between the two B-H hysteresis loops suggesting that further recrystallisation and/or grain growth has not occurred, as no improvement in magnetic properties was evident.

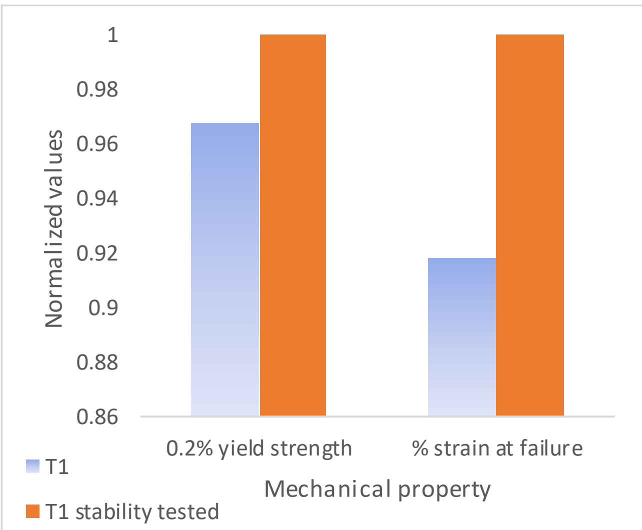

Figure 7 - Mechanical properties of T1 and T1 stability tested

Figure 7 shows very small differences in normalized mechanical property values between the T1 and T1 stability tested grade. It can be inferred the mechanical properties will persist during operation.

To further this statement, the mobility of high angle grain boundaries within the system was calculated using Equation 1 below to determine if recrystallisation would occur for longer durations an accepted approach to such a problem previous employed by [8].

$$M = M_0 \exp\left(-\frac{Q}{RT}\right) \qquad \text{Eq. [1]}$$

Where M is the mobility ($m^4s^{-1}J^{-1}$), M_0 is a constant for set reduction in thickness prior annealing (in this case 70%) Q is the activation energy kJ mol^{-1} (at 70% reduction) R is the universal gas constant and T is temperature, K.

Recrystallisation had been reported to occur in 3wt. % Si NOES from 660°C, hence the mobility of high angle grain boundaries was calculated at this temperature and compared to the mobility at 150°C. It was proposed that, should the calculated mobility of high angle grain boundaries at 150°C to be drastically lower than that at 650°C, there would be no further recrystallisation or grain growth. The mobility of high angle grain boundaries at 150°C and 650°C were 6.5E-29 $m^4s^{-1}J^{-1}$ and 4.0E-13 $m^4s^{-1}J^{-1}$ respectively which suggested long term microstructure stability during operation.

It has been shown that careful annealing optimization can produce NOES grade with improved mechanical properties coupled with slightly degraded magnetic performance. It was therefore important to determine if this magnetic/mechanical coupled effect was globally competitive with other high strength grades of NOES. For this reason, T1 and T2 normalized yield strength and normalized magnetic properties at 1.0T, 400Hz were compared to products from three different NOES producers.

The grades presented within Figure 8 vary in thickness and the link between grade thickness and magnetic loss due to eddy current losses is well understood. The stress is implicit unlike the magnetic properties and therefore a thin gauge 0.2mm thick grade that has been strengthened *via* partial recrystallisation can compete both magnetically and mechanically against thicker grades.

It shows the general positive trend between strength and magnetic loss, but also shows the coupled properties of T1 to be magnetically superior to grades from Company 2 and company 3, whilst being mechanically superior to the grades produced by Company 1. This result suggests that partial recrystallisation is a suitable strengthening mechanism with the potential to produce a globally competitive grade of high strength NOES.

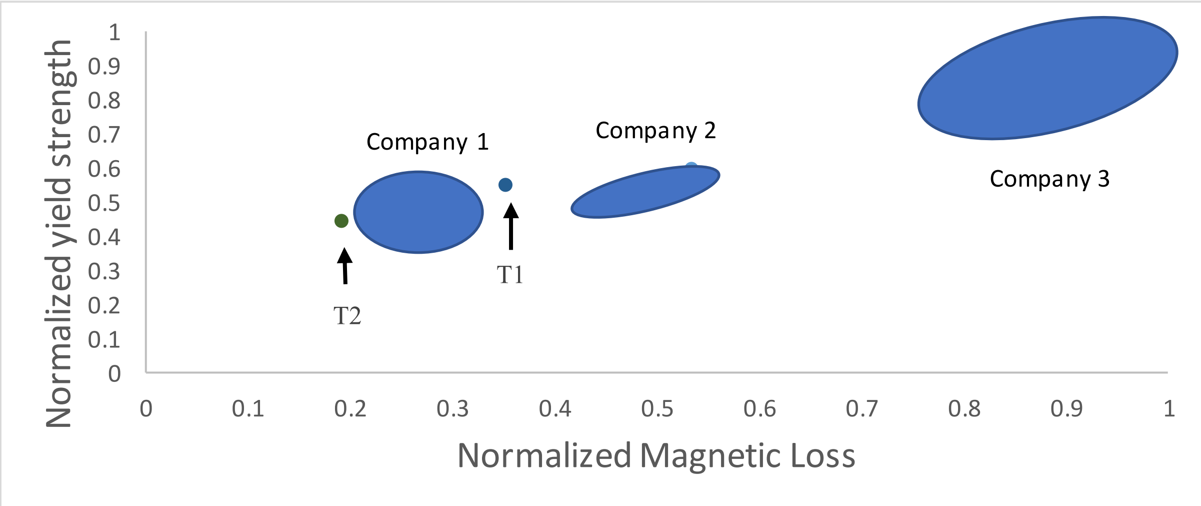

Figure 8 - Comparison of competitive company high strength NOES grade with T1 and T2

D. Conclusion

The present paper investigated the strengthening mechanism of partial recrystallisation in 3.2wt. % Si NOES and evaluated its suitability during operational conditions. The outcomes of the investigations are presented below.

- Microstructural engineering during the final annealing process can lead to a favourable proportion of recrystallisation that has the potential of producing a globally competitive high strength NOES without the need for large capital expenditure to alter manufacturing lines.
- The partially recrystallized microstructure will persist during operation. Minimal degradation of magnetic or mechanical properties during stability testing were witnessed.

E. Acknowledgements

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F. References

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