INTRODUCTION

Many important properties of ferromagnetic materials are derived from domain rearrangements during the process of magnetisation and its reversal. The microstructure of the material has been established to play an important role in this context. Thus, controlling among other factors such metallurgical variables as composition, content of impurities, recrystallisation texture and precipitation processes has gone a long way in the development of various magnetic materials.

Among the wide variety of magnetic materials, the soft magnetic steels represent an important group whose magnetisation can be easily reversed. These find use in devices like electromagnets, motors, generators and transformers. The quality of steel for such applications is usually determined by its ' core-loss'. Since the quantity of energy equivalent to core-loss is dissipated as heat, there is a major incentive in reducing such losses in soft magnetic steels.

During the useful service life of motors, generators or transformers sometimes a slow deterioration in their performance sets in which is associated with an increase in the core-loss. While at ambient temperatures it may take from a few months to a few years for such degradation to be perceptible, exposure to slightly elevated temperatures can bring about an accelerated rate of deterioration and hence can be a cause of concern. This phenomenon is termed as 'magnetic-ageing'. In fact the

the problem was so severe in the years before 1900 that transformers, whose cores were then constructed from plain carbon steels, had often to be taken apart after a few months or years of service in order to reannel the steel laminations[1]. Magnetic-ageing has therefore been recognised as an important design parameter. The present-day customers of electrical steels normally set a maximum of 5% enhancement in core-loss as the acceptance limit during an accelerated ageing test[2].

Though an analysis of core-loss in terms of its constituent parts is still a matter of some debate[3], for most practical purposes it may be thought to be resolvable into two major components : (a) eddy current loss, and (b) hysteresis loss. The former crops up owing to the existence of a large number of current-paths within the material and is dependent on its electrical resistivity. The hysteresis loss on the other hand is associated with the fact that the magnetisation process is an irreversible one where the effect (magnetisation) lags behind the cause (field). It is proportional to the frequency of the magnetising field and the area under the hysteresis loop ; the latter being approximately given by the product of saturation magnetisation and coercivity. The coercive force has been often defined as the value of the reverse magnetising field necessary to bring the intrinsic magnetisation to zero. The term coercivity refers to the coercive force of a specimen that has been previously magnetised to saturation. Owing to a sizeable material requirement and longer time consumption for direct measurement of core-loss, estimation of coercive force has alternatively been used to follow magnetic-ageing processes in laboratory investigations.

Magnetic-ageing is now generally considered to be a result of precipitation in which primarily carbon or nitrogen is involved and when their amount in solution exceeds the solubility limit at the temperature of use. During the processing of electrical steels the rate of cooling after mill-annealing is usually not sufficiently slow for the excess carbon atmos to come out during the cooling process. As a consequence, they would precipitate as fine dispersion of carbide particles when the material is in service. These precipitates interact with and pin down the domain walls preventing their smooth passage which in turn results in an increase in the coercive force. In practice, the amount of nitrogen in electrical steels is never sufficient to make any significant contribution to magnetic-ageing.

Recent investigators[4,5] have cited the analogy between mechanical hardening by second-phase particles and the development of high coercivity through domain wall pinning. The phenomenon of mechanical hardening in alloys has been investigated over the years and the mechanism is fairly well-understood in terms of the interaction of dislocations with the precipitating particles[6,7]. By comparison however, there have been fewer studies directed towards establishing a quantitative correlation between salient microstructural features and structure-sensitive magnetic properties like coercive force. Though some data involving changes in magnetic properties during ageing have been accumulated for different soft magnetic steels, corresponding observations of microstructure have been scanty. However, microstructural changes accompanying the process of quench-ageing have also contributed, though indirectly, towards some understanding of the magnetic-ageing behaviour. All these information indicate that an interplay between a number of parameters could account for this phenomenon [redacted] making a direct correlation rather difficult. It is recognised broadly that the volume fraction, morphology, habit and magnetic characteristics of the precipitate, as well as its size and distribution could affect magnetic-ageing characteristics significantly.

Addition of silicon to the grain-oriented steels to the extent of 3wt% or more is now an established practice. Silicon, through its effect of increasing the electrical resistivity, bestows the desired property of reduced eddy-current loss. The present investigation has been undertaken to examine the behaviour of magnetic-ageing in three grades of steels containing less than 2wt% silicon. The choice of the composition range was prompted on the one hand by a lack of sufficient data on magnetic-ageing in these types of steels and on the other, by the fact that a wide variety of non-oriented electrical steels contain only upto 2wt% silicon. Apart from the Si-steels, a steel containing 0.17wt% phosphorous has also been included for study to throw some light on the character of magnetic-ageing in phosphorous-bearing steels which are finding increasing use in small electrical machines. In addition to providing basic information on the variation of coercive force under a wide spectrum of ageing time and temperature conditions, it has also been thought pertinent to make a careful analysis using TEM, of the type and nature of the precipitating phases, in an effort to correlate the microstructural changes with coercive force. Furthermore, the present work attempts to bring to focus the solute-depletion process in the ferrite matrix even before the initiation of magnetic-ageing, so as to obtain some clues regarding the precipitation behaviour in general.