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# ANALYSIS OF POWER LOSS IN AS-CAST AND SURFACE TREATED AMORPHOUS RIBBON MATERIALS

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**Abstract**
*L*ocalised specific power loss was determined for surface treated Metglas® 2605SC amorphous ribbon using the initial rate of rise of temperature technique. The samples were magnetised at set flux density levels from 0.8 Tesla to 1.4 Tesla in a frequency range of 50 Hz to 400 Hz under 20 MPa tension to emulate a typical condition in a 100 kVA transformer. Annealing and polishing were found to have a marked effect on energy saving. The loss measurements verified the inhomogenity across the ribbon thickness. The energy saving was maximum if the inhomogenity was reduced by polishing both surfaces. However, a further saving was noticed on the scratched samples. The optimum scratching interval for maximum energy saving was found to be 3 mm. The anomaly factor was also found to alter due to the domain wall spacing and loss measurement. Loss separation was also attempted and hence the components of the total loss are well understood due to the physical reason which the samples were suffered. The experimental findings showed that existing theory can reliably explain the power loss in amorphous ribbon.

**Key words:** Power loss, amorphous materials, magnetic domains, transformer core

## 1. Introduction

The total power loss under alternating flux at power frequencies for both electrical steel and amorphous ribbon is an important criterion for the manufacturers and users of soft magnetic materials. The power loss can simply be explained as heat production by the electric currents induced by change of magnetisation in the material. The transformer manufacturers have introduced new transformer designs and have investigated new transformer core materials aimed at reducing core losses. Amorphous ribbon materials, because of their low core loss, have received considerable attention for use as a core material to replace silicon steel in some applications [1].

The power loss has been widely investigated theoretically and experimentally in soft magnetic materials. The theoretical attempts [2, 3] were particularly interested in the correlation of domain wall dynamics and power loss, whereas the practical studies concentrated on the effect of different physical parameters such as polishing [4], annealing [5], surface features [6], scratching [7], stress, magnetisation, etc. conditions on power loss. In theoretical studies different domain wall models have been considered. In the experimental investigations the energy saving has improved in soft magnetic materials by increasing electrical resistivity, decreasing sheet thickness, annealing, surface smoothing with polishing, decreasing domain wall spacing with optimum transverse scratching and the application of external stress or a combination of all these effects.

## 2. Components Of Total Loss

The total power loss in soft magnetic materials may be divided into three major types, namely the static hysteresis loss, $P_h$, classical eddy-current loss, $P_{ec}$ and anomalous loss, $P_a$. The most important constituent of the power loss in amorphous ribbon materials is the anomalous loss because it is responsible for up to 90% of the total power loss at power frequencies which compares to the 30% to 90% range for grain-oriented 3% silicon-iron [8].

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The loss per cycle against frequency characteristic can be extrapolated to zero frequency to obtain an estimate value of the static hysteresis loss component, $P_h$, of total loss.

The classical eddy-current loss assumes a linear B-H relationship with constant and uniform permeability throughout the material. Thus, if a sinusoidal field is applied all other quantities are sinusoidal and applying Maxwell's equations the classical eddy-current loss for a thin sheet are given as;

$$P_{ec} = \frac{\pi^2 t^2 f^2 B_{max}^2}{6\rho d} \quad \text{(W/kg)} \qquad (1)$$

where t is the thickness of the material, f is the frequency of applied field, $B_{max}$ is the peak flux density, ρ is the resistivity of the material and d is the density of the material. Then, the eddy-current loss component may be determined by subtracting the hysteresis loss from the experimentally measured total loss, on the assumption that for thin lamination. However, when this is done it is invariable found that this apparent eddy-current loss is much more greater than its value as calculated from Equ. (1).This led to the suggestion that further component of loss exists which is termed the anomalous loss. The causes of anomalous loss in 3% silicon-iron and amorphous ribbon materials have been compared [9]. The origin of anomalous loss in amorphous ribbon materials can be attributed to many causes particularly, non-sinusoidal, non-uniform and non-repetitive domain wall motion.

A convenient method to define the magnitude of the anomalous loss compared to the classical eddy-current loss is the anomaly factor. Although, the classical eddy-current loss is calculated by the assumption such as uniform material, constant permeability, etc. but neither of these assumptions is correct due to the existence of domain walls and inhomogeneous material. Theoretical predictions of increase in the classical eddy-current loss due to the existence of domain walls have been made by Pry and Bean [10].
Pry and Bean suggested that the value of anomaly factor, $\eta_D$, from domain wall observations is simply given as;

$$\eta_D = 1.63\,\frac{\text{domain wall spacing}}{\text{material thickness}} \qquad (2)$$

The anomaly factor, $\eta_{PL}$, may also be defined from the power loss measurements as;

$$\eta_{PL} = \frac{P_{total} - P_{hysteresis}}{P_{eddy\ current}} \qquad (3)$$

### 3. Experimental Procedure

*1) Sample preparation:* The samples were cut to dimensions of 30 mm x 12.7 mm x 0.028 mm from Metglas® 2605SC with a chemical composition of $Fe_{81}$ $B_{13.5}$ $Si_{3.5}$ $C_2$ manufactured by Honeywell Co., USA. Samples either bright surface (contact to air during solidification), rough surface (contact to drum during solidification) or both surfaces polished were polished to obtain smooth surface like mirror. Some of the polished samples were scratched with different scratching interval. The samples were annealed at 360 °C for 2 hours in vacuum to remove the internal stresses brought about by the polishing process and then bloomed with ZnS. The sample investigated included;

1) as-cast (as received),
2) annealed unpolished,
3) bright surface polished, annealed and bloomed,
4) rough surface polished, annealed and bloomed,
5) both surfaces polished, annealed and bloomed,
6) both surfaces polished, 7 mm interval scratched, annealed, and bloomed,
7) both surfaces polished, 3 mm interval scratched, annealed and bloomed and
8) both surfaces polished, 1 mm interval scratched, annealed and bloomed samples.

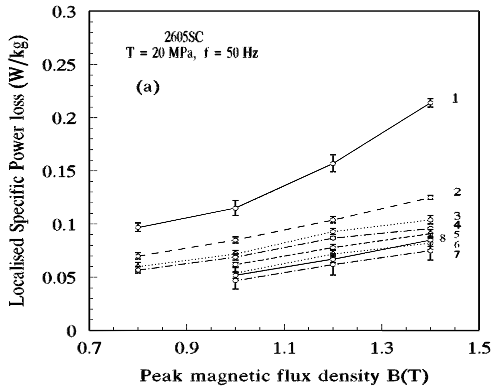
*2) Domain observations:* The static domain observations were carried out on these treated samples to perform anomaly factor, $\eta_D$, calculations [6, 7]. The longitudinal Kerr effect was used to observe domains under uniform tension applied along the ribbon length. The domain observation is not possible on unpolished samples using the Kerr effect technique even when the sample is properly annealed for stress relief. However, this problem was overcome by polishing a small area on the sample surface for domain observation. The domain observations on these samples may emulate the domain wall spacing measurements and anomaly factor, $\eta_D$, calculations on annealed unpolished samples.

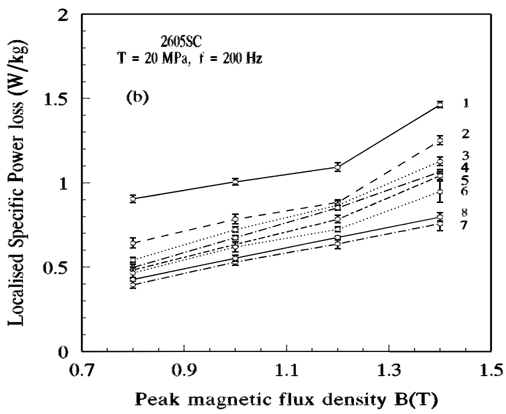
*3) The localised specific power loss measurements:* The localised specific power loss measurements were made on as-cast as well as surface treated samples (annealed, polished and scratched) using the initial rate of rise of temperature technique [11]. The samples were magnetised sinusoidally from 0.8 Tesla to 1.4 Tesla in a frequency range of 50 Hz to 400 Hz. The measurements were taken under 20 MPa tension to emulate the typical condition of 100 kVA transformer.

## 4. Results

The measurements were carried out on various surface treated 2605SC ribbons in order to clarify the influence of surface properties, polishing, annealing, scratching and thickness on power loss. Fig. 1 (a), (b) and (c) indicate that the variation of localised specific power loss with peak flux density at 50 Hz, 200 Hz and 400 Hz, respectively. Although, the energy saving was much pronounced between the as-cast and annealed samples it was not significant amongst polished and scratched samples. The lowest localised specific power loss was obtained on 3 mm interval scratched samples.

In Fig. 2 (a), (b) and (c) the localised specific power loss was drawn as a function of scratching interval at 50 Hz, 200 Hz and 400 Hz, respectively. The domain structures in amorphous ribbon were studied in the previous papers [6, 7]. The domain observations on unstressed samples showed a complex leaf domain structure. Therefore, the domain wall spacing measurements throughout the sample can not be performed on unstressed samples. The domain structure on samples under tension is much simpler to explain. They were found to consist of large flux carrying 180° bar domains in the stress direction (along the ribbon length). So, the meaningful domain wall spacing measurements were carried out on the samples under tension. The domain wall spacing obtained from unmagnetised Metglas® 2605SC scratched samples with different scratching intervals and from unscratched samples are tabulated in Table 1. The domain wall spacing to thickness ratio affects the loss measurements. The anomaly factor, $\eta_D$, calculated static domain observations are also given in Table 1.



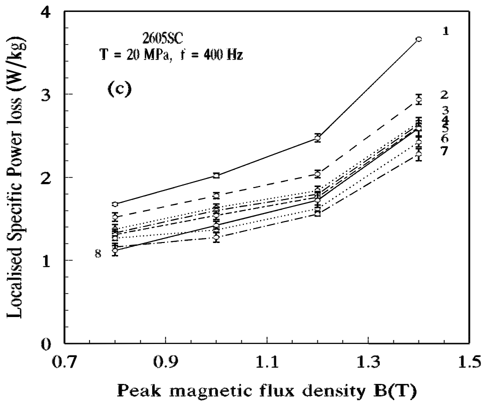



**Figure 1.** The variation of localised specific power loss with peak flux density on 2605SC amorphous ribbon at (a) 50 Hz, (b) 200 Hz and (c) 400 Hz, under 20 MPa tension.

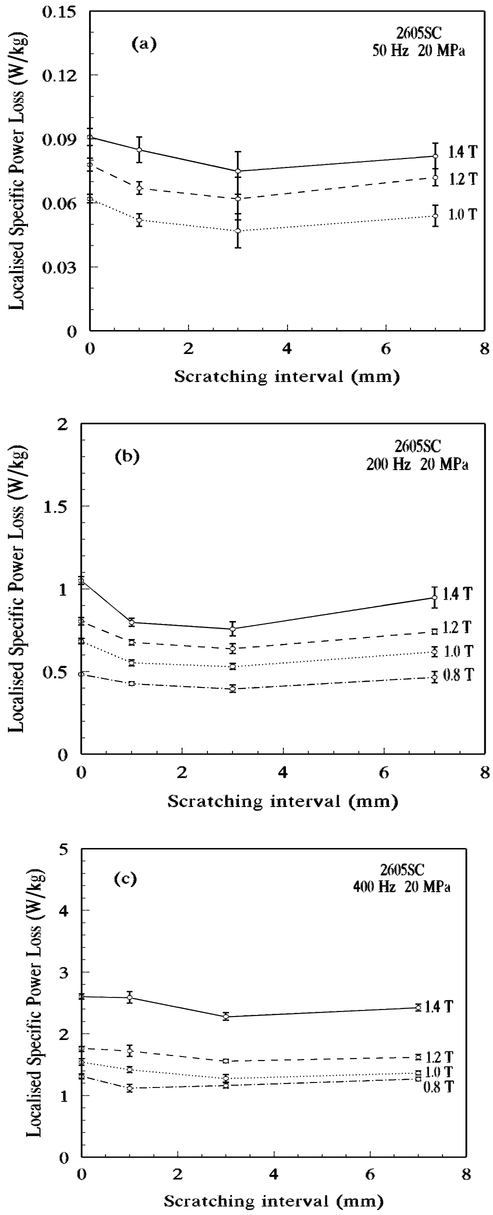



**Figure 2.** The variation of localised specific power loss with scratching interval on 2605SC amorphous ribbon at (a) 50 Hz, (b) 200 Hz and (c) 400 Hz, under 20 MPa tension.

The largest average domain wall spacing was measured on both surfaces polished, annealed and bloomed samples and the smallest one on scratched samples with 1 mm interval. In Table 1 the average domain wall spacing is reduced due to the increasing scratching interval amongst the scratched samples.

## 5. Discussion

*1) Domain structure:* The transverse scratching of the sample caused the domain refinement. It is attributed to the theory that the transverse scratching on the surface will induce the formation of transverse domains on a scratched surface. These transverse domains serve to split the longitudinal domain, thereby reducing the magnetostatic energy.

*2) The localised specific power loss:* The localised specific power loss can be discussed in terms of: the effect of annealing, the influence of thickness and scratching, loss components and anomaly factor.

The drum quenching and polishing process introduce large stresses both compressive and tensile which can be relieved by sufficient annealing conditions in the amorphous ribbons [4, 5]. One drawback is that the annealing tends to degrade the mechanical properties of the ribbon in particular after annealing at a temperature necessary to produce complete stress relieving the samples become more brittle. The measured loss results presented in Fig. 1 confirm that the stress relief by heat treatment has a marked effect on the highly magnetostrictive amorphous ribbons to reduce power loss. At high flux density levels large reductions in loss of typically 40% between the as-cast and annealed samples at 50 Hz, 0.8 Tesla were obtained, Fig. 1(a). The energy saving was about 20% on the annealed samples as compared to as- cast state at 200 Hz and 400 Hz, respectively at 1.4 Tesla. However, it was about 10% at low flux density 0.8 Tesla, 400 Hz, Fig. 1(c). This improvement in energy saving is related to the structural relaxation which occurs by a sufficient atomic re-arrangement in the sample as compared to the as-cast state, i.e. reducing the anisotropy by re-arrangement of the domain structure and increasing the magnetic softness in the induced easy direction of magnetisation along the ribbon length under tension.

**Table 1.**The variation of average domain wall spacing and anomaly factor, $\eta_d$, on different surface treated metglas® 2605SC unmagnetised amorphous ribbon under 20 MPa tension

| Sample surface details | Average domain wall spacing (mm) | Anomaly factor ($\eta_D$) |
|---|---|---|
| annealed unpolished | 0.61±0.006 | 34.3±0.3 |
| bright surface polished only | 0.54±0.008 | 36.7±0.5 |
| rough surface polished only | 0.62±0.007 | 42.1±0.5 |
| both surfaces polished | 0.76±0.009 | 61.9±0.7 |
| 7 mm interval scratched | 0.51±0.008 | 41.6±0.7 |
| 5 mm interval scratched | 0.47±0.009 | 38.3±0.7 |
| 3 mm interval scratched | 0.35±0.009 | 28.5±0.7 |
| 1 mm interval scratched | 0.24±0.008 | 19.7±0.7 |

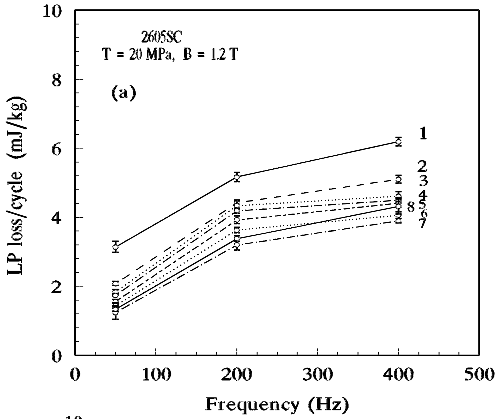
The polishing effect in energy saving on iron-based amorphous ribbon materials was extensively investigated in the past [4]. The smooth surface implies less pinning effect and more uniform domain wall motion. The pinning effect causes an additional loss due to induced localised eddy-current whereas, the uniform domain wall motion reduces the power loss.

Some structural inhomogenity exists across the ribbon thickness [12]. The localised specific power loss measurements confirmed the structural inhomogenity in the ribbon. The lowest power loss was measured on both surfaces polished, followed by rough surface polished only and the highest loss was detected on the bright surface polished only amongst the polished annealed and unscratched samples, Fig. 1 [6]. This reduction in loss improved to 58% on both surfaces polished ribbon as compared to as-cast ribbon at 50 Hz, 1.4 Tesla, respectively. The improvement in loss at high frequency and high flux density was not as high as at low frequency. About 28% reduction in loss was detected on the same ribbon as compared to as-cast ribbon at 400 Hz, 1.4 Tesla, Fig.1. The element concentration in analysis of the samples showed that it is not uniform across the ribbon thickness. Particularly, iron concentration of the ribbon which is important for magnetic properties, is minimum at the centre of the ribbon and increasing towards one edge.

The domain refinement is the one of the methods for energy saving due to the reduction of the domain wall spacing. There is a considerable gap amongst scratched and unscratched samples, Fig. 1. About 90% reduction in loss was measured between the as-cast and 7 mm interval scratched samples at 50 Hz, 1.4 Tesla, respectively. A further 8.5% lower loss was detected on 3 mm interval scratched samples. So, maximum 98.5% energy saving was achieved by scratching of both surfaces polished samples which is a huge economic saving on power or distribution transformers between the as-cast and 3 mm interval scratched samples.

The loss measurements on 1, 3 and 7 mm interval scratched samples showed that 3 mm interval was the optimum scratching interval for maximum energy saving, Fig. 2 (a), (b), (c). When the scratching interval decreased to 1 mm a higher loss detected. Also, 7 mm interval scratched samples have higher losses than 3 mm interval scratched samples. Hence, a 3 mm interval is found to be optimum interval. The reduction by scratching is, of course, attributed to the reduction in domain wall spacing. About 15-25% reduction on power loss was reported on annealed and scribed samples either using mechanical or thermal methods to scribe the samples without optimising any parameters. The data obtained from Fig. 1 and Fig. 2 confirms that maximum reduction in loss was measured at 50 Hz due to the scratching. It must be considered that during the domain refining process every extra domain adds an additional energy, so the optimum scratching interval is a compromise between the domain wall energy and induced stresses caused by scratching on the sample. Table 1 shows although, the average domain wall spacing due to the scratching interval is smaller on 1 mm scratching samples than 3 mm scratching samples a higher loss was detected on 1 mm scratched samples.

Finally, the loss components and anomaly factor which makes a good correlation between the power loss and domain wall spacing, will be discussed. The loss measurements in a range of frequencies were needed for loss separation and anomaly factor calculation from loss measurements. Fig. 3 shows the localised specific power loss per cycle against frequency characteristics. These characteristics can be extrapolated to zero frequency to obtain an estimate of the static hysteresis component, $P_h$, of total loss. The classical eddy-current component, $P_{ec}$, of total loss can be calculated by using (1). This relationship enables the value of the anomalous loss component to be determined.



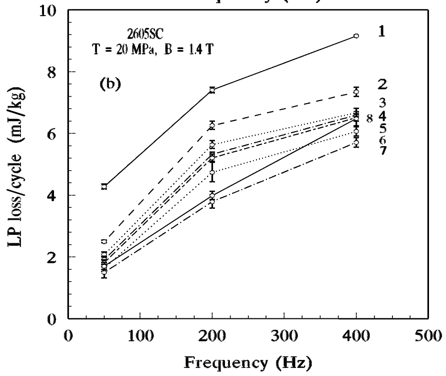




**Figure 3.** The variation of localised specific power loss per cycle with frequency on 2605SC amorphous ribbon at (a) 1.2 Tesla and (b) 1.4 Tesla under 20 MPa tension.

The anomaly factor can be analysed amongst the surface treated samples which are the bright, rough, both surfaces polished and 1 mm, 3 mm and 7 mm interval scratched. The anomaly factor is higher on bright surface polished only samples than rough surface polished only samples. The highest anomaly factor was found on both surfaces polished samples. It is believed that the structural inhomogenity across the ribbon thickness should be responsible. The domain observations [14] and element concentration [6] in the ribbon confirm these findings. On both surfaces polished samples these inhomogenous regions near surfaces was removed by polishing and the domain walls moved easily during the magnetisation of the sample. The loss measurements verified that the anomalous loss component of total loss amongst the polished samples has the biggest value on both surfaces polished ribbon as compared to the others. It may be explained that the static hysteresis component has the lowest value on these samples. One of the reasons for the static hysteresis component is that the material must have a low surface imperfections and impurity level [1]. These conditions are provided in the case of both surfaces polished samples by means of removing the inhomogenous regions near surfaces. The maximum (83%) static hysteresis loss of total loss on as-cast samples was found at 50 Hz 1.2 Tesla, respectively. The anomalous loss constitutes the major part of the total loss on both surfaces polished sample. It is considered that the anomalous loss must be related to domain wall motion on the surfaces [15]. The smooth surface also cause the reduction in the static hysteresis loss due to the surface imperfections. The classical eddy-current component was also the lowest value due to the thickness of the ribbon. The ratio of the static hysteresis loss to total loss is reduced to 13% at 400 Hz, 1.4 Tesla on both surfaces polished ribbons. Although, the anomalous loss component increased to 88% at 400 Hz, 1.4 Tesla on the same ribbons. The anomaly factor increases with increasing flux density. The increasing anomaly factor due to the flux density depends on the domain width. From domain observation the domain width is increased with flux density. This implies that the large domain size affects directly the loss in the material.

The domain observation could not be performed at high flux densities, due to the surface saturation of the ribbon. However, the anomaly factor calculated from the loss measurements also increased at high flux densities which confirms the trend of results obtained from the domain observation. A small anomaly factor was calculated at higher frequencies. This can be firstly anticipated due to the increase in the classical eddy-current component of the loss and secondly the inhomogenous structure near surfaces of the ribbon. The decreasing of the anomaly factor due to the classical eddy-current also originates from the magnetising frequency as it is proportional to the square of it. However, it is very small as compared to the static or anomalous loss components.

It is clear that domain refining affects the anomaly factor due to the reduction in the domain wall spacing. It causes a further reduction on the anomalous loss. But, an optimum scratching interval must be reached for maximum energy saving amongst the scratched ribbons. The optimum scratching was found 3 mm which provides over 9% reduction in anomalous loss between both surfaces polished and 3 mm scratched samples.
In amorphous ribbon materials complete flux penetration may take place but the structural inhomogenity across the ribbon thickness or some physical parameters such as inclusions, defects, imperfections, etc. cause the domain wall angle and wall bowing. The difference amongst the anomaly factors can be clarified the non-sinusoidal, non-repetitive and non-uniform domain wall motion in amorphous ribbon materials. The deformed domain wall motion is attributed to the pinning, surface defects, scratches (longitudinal direction of the ribbon), cracks, non-magnetic inclusions and structural inhomogenity across the ribbon thickness or a combination of all these effects. The harmonic of magnetising waveform can also be considered for large variation of anomaly factors.

The structural inhomogenity (element concentration) is strongly responsible for high anomalous loss in amorphous ribbon materials. Therefore, the importance of producing metallurgically homogenous material can be highlighted in sinusoidal, repetitive and uniform domain wall motion hence energy saving in anomalous loss. However, as it is not easy to control all of the process of metallurgically homogenous magnetic material, the physical effects such as polishing, annealing and surface scratching are the best available options for improving energy savings in existing materials.
Comparison shows that conventional theories relating in domain wall motion and loss are even less applicable to amorphous ribbons than they are to conventional electrical steels. The anomaly factors also verify the suggestion that poor domain wall dynamics are responsible for the majority of losses which is the anomalous loss component of the total loss. However, it can be suggested that in order to find the total loss as;

$$P_T = P_h + P_{ec} + (P_D + P_{un})_a \quad (4)$$

The anomalous loss can be divided into two parts such as $P_D$ and $P_{un}$. $P_D$ may be determined using the Pry and Bean model [10] from domain observations. $P_{un}$ is called the undefined losses coming from all the physical parameters. Bertotti, Fiorillo and Appino [3, 16] attempted to explain by considering each domain wall to cause loss in the material and hence overall losses. However, in practice it is very difficult to find where these domain walls are located and how many there are due to stress sensitivity, non-repeatability and inhomogenous structure of amorphous ribbon materials. Therefore, the older theory is better for understanding the anomalous loss component of the total loss of amorphous ribbon.

## 6. Conclusions

The major part of the total loss is the anomalous loss in amorphous ribbon. The structural inhomogenity is strongly responsible for the non-sinusoidal, non-repetitive and non-uniform domain wall motion which are the origin of high anomalous loss. The physical effects such as polishing, annealing, surface scratching are the best available options to give maximum energy saving in the existing soft magnetic materials. Over 92% reduction in loss was obtained on both surfaces polished annealed and 3 mm interval scratched ribbons as compared to as-cast ribbons.

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