

Carbon content control during the production process of high carbon brake discs

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Abstract

The physical properties of high carbon brake discs are strongly affected by the content of this element, including the ability to dissipate the heat produced during the braking of the vehicle. In the normal manufacturing process there is a decrease in the carbon percentage, with regard to the original content registered in the furnace. During the course of this study, the variables that have any influence on this loss of carbon have been obtained. As a consequence, a mathematical model has been developed which identifies, in a precise manner, the carbon percentage in each of the process steps. This enables its use at any time, without the need for additional controls, resulting in cost and logistics savings, ensuring the fulfilment of the material requirements.

Introduction

Brake discs made of cast iron with high carbon content present some physical properties suitable for high temperature applications, especially those related to the thermal dissipation, distortion and cracking occurring due to thermal effect, and collapse by vibration^(1,2).

The matrix structure of such discs should be completely pearlitic. The presence of small traces of ferrite reduces the wear resistance and fracture toughness. Despite this, according to some researchers, some small amounts of ferrite can be associated with an increase in the thermal

conductivity⁽³⁾.

This pearlitic matrix structure is obtained by alloying element additions⁽⁴⁾, which stabilise the pearlite, thereby increasing the mechanical properties. It is very important to maintain a very well balanced ratio of these elements due to the increase in cost and material hardness (which creates machining problems)⁽⁵⁾.

The carbon and silicon content plays an important role in the ultimate tensile strength of grey iron castings. The silicon content should be enough to ensure the precipitation of carbon as graphite lamellae, and the lowest possible quantity to restrict to the maximum the ferrite appearance⁽¹⁾. The carbon content must be kept at the lowest limit of the specification, since unnecessary high amounts of it, ostensibly lowers the ultimate tensile strength⁽⁶⁾.

Given these considerations, it is essential to carry out a precise control of the carbon content throughout the production process in order to ensure the standards of chemical composition and mechanical properties, thus allowing the optimum minimalisation of addition of alloying elements.

Carbon and silicon oxidation reactions

Carbon loss is primarily associated with the presence of oxygen. The great affinity between them (especially at high temperature) leads to their combination to form carbon monoxide (CO) or carbon dioxide (CO₂).

The oxygen content in the base iron is related to the melting process (type of furnace), varying between 40 and 100 ppm for induction furnaces. However, the active oxygen content (not combined oxygen) is much smaller, oscillating between 1.5 and 5.0 ppm.

The active oxygen content varies throughout the subsequent production processes. Its content increases during the pouring processes (from the furnace to the ladle, from the ladle to the pouring unit and during the pouring into the mould), and decreases in the inoculation process. This is because the oxygen level of the iron depends on the balance existing between the reactions of this element with other elements found in the liquid iron, with the compounds present in the slag and with the compounds added at different steps of the process.

Oxygen in the molten metal comes from three main sources:

- Raw materials, which include both wet or rusted metallic charges and the oxygen contained in the additives introduced (re carburisers, ferroalloys, etc.).
- Reactions between the melt and the refractory.
- Melt reactions with the atmosphere in the melting, pouring, holding in the pouring unit and pouring into the moulds.

The temperature also influences the decarburisation process. The higher it is, the more oxygen the metal is able to absorb, and therefore, a higher carbon content can get combined with the oxygen.

In the same way, the longer the metal is at high temperature, the more carbon is lost through oxidation. When carbon oxidises, the amount of

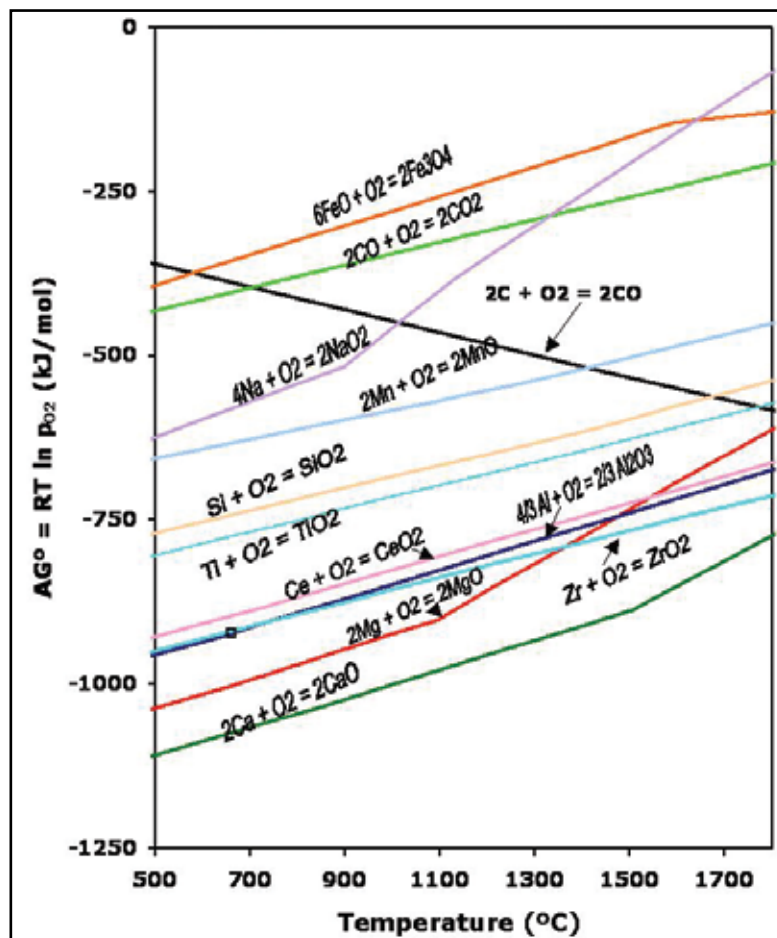


Fig. 1 Ellingham diagram of oxide formation

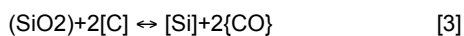
oxygen in the iron decreases. The system tends to return to its steady state, acquiring oxygen from the atmosphere and oxidising a greater amount of carbon. The atmosphere is a great source of oxygen, and the slag can act as a barrier between both, by blocking the absorption of oxygen by the liquid metal.

According to the Ellingham diagram, in the absence of significant amounts of calcium, magnesium, zirconium, aluminium, cerium and titanium, the element that is more easily oxidised at low temperatures is the silicon, and at high temperatures the carbon. This is because the required Gibbs free energy of formation of the CO compound has an opposite slope to that of the silicon oxidation, and therefore, its formation is more stable at high temperatures (fig. 1).

Thus, at elevated temperatures, due to the high carbon content, it oxidises (according to reaction⁽¹⁾), forming CO bubbles which pass through the melt to the atmosphere, so the amount of carbon decreases. By decreasing the temperature, below the so-called equilibrium temperature, the silicon is the element which oxidises, forming SiO₂.

The result obtained of adding up the equations for carbon oxidation [1] and silicon reduction [2], is the reaction [3]. The equilibrium temperature for this reaction can be determined from carbon and silicon concentrations in the melt.

The components in square brackets are dissolved in the liquid metal, the ones in brackets are part of the slag and the ones shown in braces correspond to a gas phase.



From this equation [3], the equilibrium temperature is obtained, according to the equation [4]⁽⁷⁾.

$$T_{eq} (^{\circ}C) = \frac{-27486}{\log \left(\frac{[Si]}{[C]^2} \right) - 15.47} - 273 \quad [4]$$

In this way, when the temperature is higher than that for equilibrium, the oxidation of carbon is the predominant reaction, whereas, if lower, the silicon is the element that gets oxidised.

Under these conditions, the element that gets oxidised at high temperatures is the carbon, giving off CO in gaseous form. However, at low temperatures the silicon gets oxidised, forming a larger amount of slag, which is due to the SiO₂ occurring in solid form. Furthermore, the higher the equilibrium temperature, the more it favours the formation of slag during the cooling of the liquid metal.

The equilibrium temperature ranges from 1400 to 1430°C for the usual compositions of grey iron castings, being 1410°C the temperature for a common composition for the production of high carbon discs (3.80 wt % carbon and 2.00 wt % silicon).

Experimental methodology

Carbon is probably the most difficult element to control in graphitic cast irons. In this paper, two of the most

reliable techniques currently available in the market have been used: the recording of the cooling curve for a white cast iron (Thermolan®), and carbon analysis by combustion (LECO).

Both techniques have been used in every step of the process: melting shop (furnaces), transfer ladle, pouring unit and in the castings themselves.

First, the cooling curves are recorded using two standard cups with different additives:

- Tellurium: drives the solidification according to the metastable system (white iron), which allows determination of the carbon and silicon content.
- Inoculant: the 0.10 wt % is manually added in order to reproduce in all the steps of the process the same conditions the castings have (which are stream inoculated).

Afterwards, the carbon of the inoculated standard sample (cup) is analysed by combustion. The aim is to obtain the carbon content deviations during the production process, obtaining the loss of it from the melting shop to the castings themselves.

The melting shop consists of two medium frequency induction furnaces, whose capacity is 17 t. They usually work according to the full-empty pattern. In some cases two ladles (2.5 t per ladle) have been extracted from them, recharging the extracted 5 t.

Additionally, in some cases, the holding time at high temperatures has been increased, whether the furnace is full, half full or almost empty.

The charge of the furnace consists of a heel (~2 t), where 5 t of automotive steel scrap, 10 t returns, petrol recarburiser, CSi and FeSi have been added. The final adjustment of the carbon percentage is made using graphite electrode.

The melt iron is poured from the furnace to the transfer ladle. The carbon content has been checked in every extracted ladle, with the aim of knowing the variation of the carbon percentage during the emptying of the furnace.

The pouring unit tests have been performed on two vertical moulding lines (Disamatic).

- In the first one, the transfer ladle also acts as a pouring ladle. The tests are carried out at the beginning and at the end of each ladle.
- In the second one, the molten metal from the transfer ladle is poured into a gas heated furnace (~7 t of capacity). The tests are carried out two minutes after pouring the metal from the ladle (in order to assure the homogeneity of the metal) and just before the pouring of the following ladle.

Carbon analysis by combustion has been made in several properly marked and identified castings. The target is to know the total carbon losses (from the melting shop to the castings themselves).

In total, 22 furnaces, 112 ladles, 63 measurements in the pouring unit and 31 castings have been analysed.

Results and discussion

The carbon content obtained during the emptying of the furnaces A and B is shown in fig. 2. A downward tendency of the carbon percentage can be appreciated (only the most representative trials are included so as to make the image clearer).

It should be noted in fig. 2, the emergence of upward tendencies which can not solely be attributed to the uncertainty of the measurement system, because the carbon analysis by combustion (LECO) shows the same tendency. The cases showing a bigger increase in the percentage of carbon

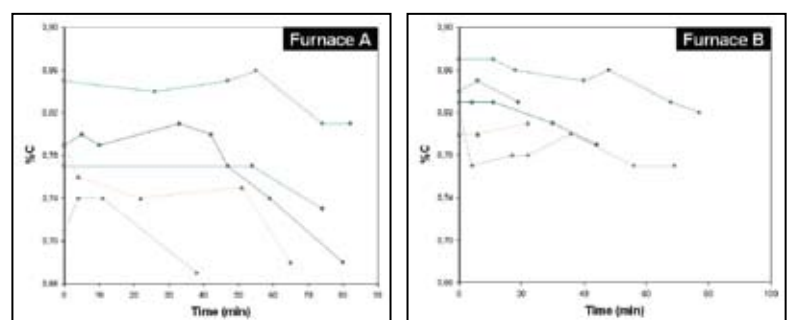


Fig. 2 Evolution of the carbon percentage of some of the furnaces analysed

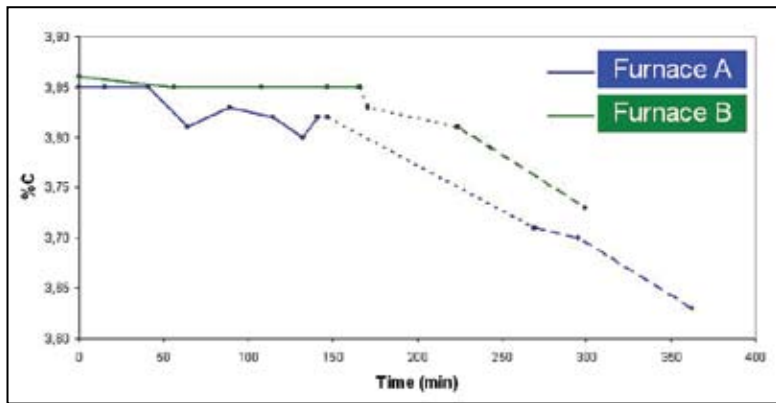


Fig. 3 Evolution of the carbon percentage after long holding time in different conditions: full furnace (solid line), after extracting two ladles (dotted line-short dots) and after extracting four ladles (dotted line-long dots)

correspond to furnaces that had been adjusted in the last moment.

As can be seen in fig. 2, the carbon losses are bigger in the latest ladles of the furnace. To understand the influence of the holding time with different amounts of residual metal in the furnace, two tests (one per furnace) have been carried out. They have consisted of maintaining the melt at high temperatures during a certain period of time when the furnace was full, and when two and four ladles have been extracted (fig. 3).

The loss of carbon is not the same under the different conditions mentioned, which can be associated to:

- The contact surface between the melt and the atmosphere varies (being bigger when the furnace is more tilted).
- Increased agitation of the melt.

Both factors increase the concentration of oxygen in the melt. As in the normal tests performed before, there was a small increase in the percentage of carbon after extracting the first ladles.

The usual practice in foundries consists of analysing the carbon content of the furnace when it is full. Later it is very difficult to obtain a sample. From this study it is possible to extract an equation to know the carbon percentage at any moment of time (% C_i) from its initial content, from late recarburation, from the extracted number of ladles and from the time passed (in minutes), as shown in equation 5, where the 'K_x' parameters correspond to the coefficients of adjustment and 'Z' depends on whether a late recarburation as been needed. The degree of agreement between the results of this expression and experimental results is shown in fig. 4.

$$\%C_i = K_1 \cdot Z \cdot \%C_{\text{Initial}} + K_2 \cdot \text{No. extracted ladle (min)} + K_3 \quad [5]$$

The loss of carbon in the transfer/pouring ladle can be considered to be approximately 0.03% for the holding times used in this study (~15 minutes). Under normal production conditions, this time can not be greater due to the limitation that causes the loss of temperature and which affects the pouring of the castings.

The carbon content analysis in the pouring unit (p.u.) corresponding to the gas heated furnace, at the beginning and at the end of the pouring of a ladle, leads to obtain a prediction equation (equation 6) for the percentage of this element, based on the initial content and on the holding time (in minutes). K_x parameters correspond to the adjustment factors. The degree of agreement between this prediction and the data recorded is shown in fig. 5.

$$\%C_{\text{Final p.u.}} = \%C_{\text{Initial p.u.}} + K_4 \cdot \text{time (min)} + K_5 \quad [6]$$

Finally, the carbon content in the pouring unit has been related to the one obtained in the castings themselves by equation 7, where also the parameters K_x correspond to the adjustment factors. The comparison between the carbon calculated by the equation and that obtained by combustion analysis (Leco) in the castings is shown in fig. 6.

$$\%C_{\text{Casting}} = K_6 \cdot \%C_{\text{p.u.}} + K_7 \quad [7]$$

Joining all the estimated equations to determine the carbon loss in each step of the process, identifies the final carbon percentage in both, the

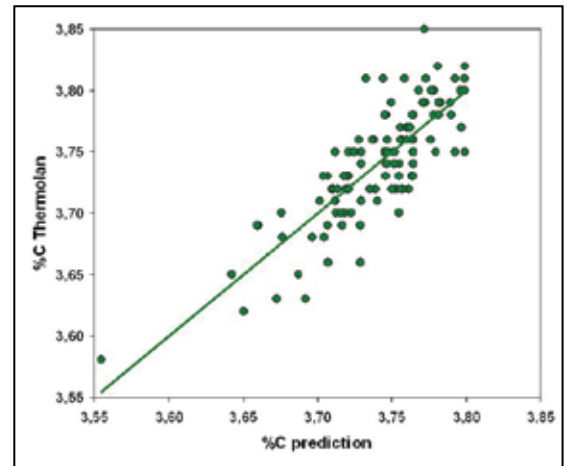


Fig. 4 Relationship between the carbon obtained from prediction and provided by Thermolan®

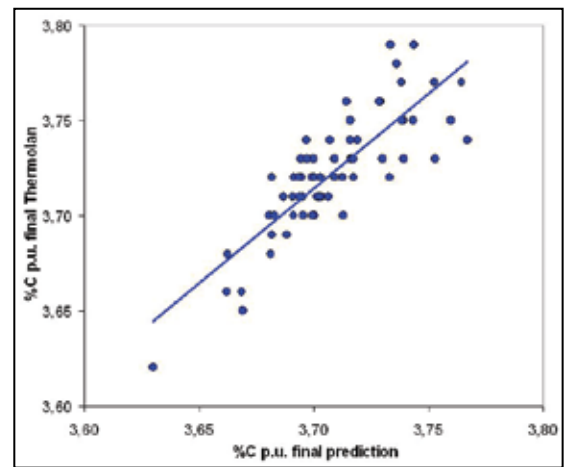


Fig. 5 Relationship between the %C obtained by the prediction and provided by Thermolan® in the pouring unit

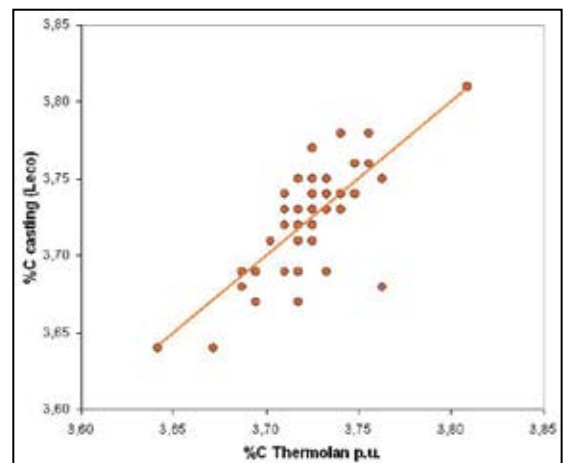


Fig. 6. Relationship between the %C in the pouring unit (Thermolan®) and the one obtained in the casting (Leco)

pouring unit (fig. 7) and in the casting itself (fig. 8) only determining the carbon content in the furnace, with an error of ±0.05%.

Conclusions

- The decarburation process can be associated with the combination of this element with the free oxygen present in the melt. Carbon monoxide (CO) is formed and it goes to the atmosphere.

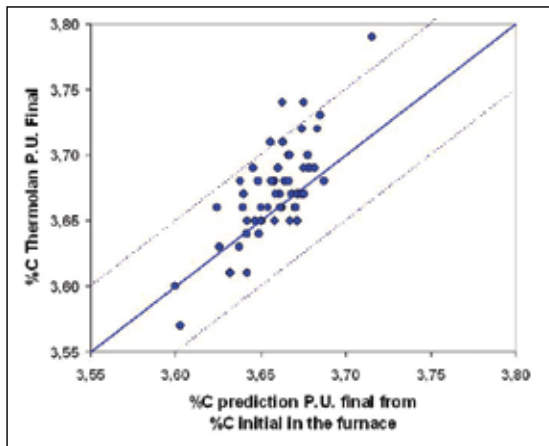


Fig. 7 Relationship between the %C predicted in the pouring unit from the initial carbon content in the furnace and the one provided by Thermolan® in the same pouring unit

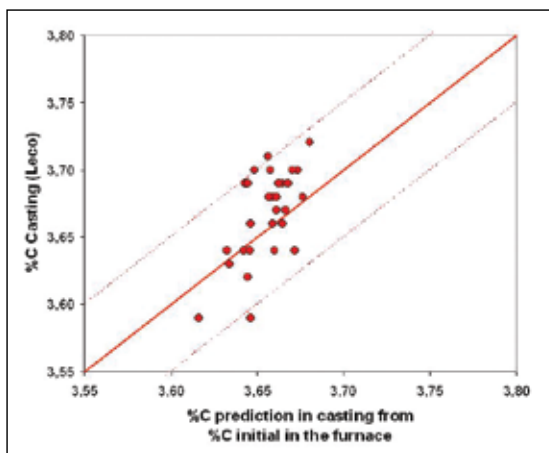


Fig. 8 Relationship between the %C in the casting itself predicted from the initial carbon content in the furnace and the one obtained in the casting itself by combustion technique

- The carbon loss in the furnace depends on the holding time and on the amount of metal remaining in the furnace. The emptier it is the greater melt-air interface there is, and the higher the loss is when

increasing this ratio.

- While some cases have been observed when the carbon percentage increases at the beginning of the emptying of the furnace, it can be associated with late recarburations or late recarburiser adsorption, which are favoured by the agitation of the metal.
- Carbon is lost in each pouring (from furnace to the ladle, from the ladle to the pouring unit and while pouring the moulds) and in the pouring unit. In this last case the losses can be also associated to the holding time.
- An equation that determines the percentage of carbon in each step of the process has been achieved. This reveals the amount of this element with regards to the initial carbon content in the furnace, the number of ladles extracted, the time, and the recarburisation adjustment made. This also identifies the controls of this element and allows one to act and optimise the amount of carbon in real time.
- This proper control of carbon enables the minimisation of both the production of discs that do not fulfil the specification (and therefore decreases the rejection rate), and the need of adding alloying elements in order to obtain the desired mechanical properties.
- The knowledge of the final carbon content in the casting itself with an error less than 0.05% is within the error committed by the measurement system (stipulated at about 0.05% for both the thermal analysis and combustion analysis techniques).

References

- Oluwadare G O, Atanda P O, 'Effect of processing parameters on the microstructures and properties of automobile brake drum'. Journal of applied sciences 7 (17): 2468-2473, 2007.
- Rukadikar M C, Reddy G P, 'Influence of chemical composition and microstructure on thermal conductivity of alloyed pearlitic flake graphite cast irons'. Journal of materials science, 21, 4403-4410, 1986.
- Guesser W L, Masiero I, Melleras E, Cabezas C S, 'Thermal conductivity of gray iron and compacted graphite iron used for cylinder heads'. Revista Matéria, vol.10, no. 2, pp. 265-272, June 2005.
- Álvarez L, Luis C J, Puertas I, 'Analysis of the influence of chemical composition on the mechanical and metallurgical properties of engine cylinder blocks in grey cast iron'. Journal of materials processing technology, vol. 153-154, pp. 1039-1044, 2004.
- Krause D E, 'Gray iron - a unique engineering material'. Gray, ductile and malleable iron castings current capabilities, ASTM STP 455. American Society for testing and materials, Philadelphia, 1969, pp. 3-28.
- Metals handbook, ASM, 2nd, Desd ed, 1998.
- Müller J, Schock D, Wolf G, Giessereiforschung, 52, no. 3, pp. 77-94, 2000.

Design Guide on Cast Irons

A new design guide, for use by engineers and designers, has been published by BSI. 'Cast irons. Part 1: Materials and properties for design', (ref PD ISO/TR 10809-1:2009) has been prepared by a working group from ISO committee TC 25, under the chairmanship of ICME Fellow, Martin Fallon cEng, and contains technical information to help the designer better understand this most complex of materials.

Informative and accessible at just over 50 pages, the guide covers all the main grades in the cast iron family, including compacted graphite cast iron, CGI, ausferritic (austempered) ductile cast iron, ADI, abrasion resistant and austenitic cast irons as well as the better known grey cast iron and spheroidal graphite (also termed ductile or nodular graphite) cast iron. It also includes, usefully, a short section on why certain types of cast iron should be considered and some examples of applications for cast irons.

The guide will help to dispel many of the myths about cast iron as the range of properties that are available from within the family of cast irons are clearly demonstrated. For example the fact that strengths of up to 1100 Nm⁻² are possible for an ADI grade, and that spheroidal graphite irons are available that have ductilities of over 22%. There are also four grades of ductile cast iron that are specified with minimum impact values at with -20°C or -40°C. Also noted is the fact that grey cast irons have excellent thermal and damping properties and are also good in compression which will make them highly suitable for certain applications whilst being unsuitable for applications where ductility is required.

Designers who are unfamiliar with cast iron as an engineering material should find the guide informative since, as well as providing the basic mechanical property information for the various grades, the guide also includes information about section sensitivity, particularly relevant for grey irons, general and specific metallurgy and heat treatment.

Whilst aimed predominantly at engineers and end users of cast iron, the guide also will be invaluable for foundrymen producing cast iron components who wish to have a better understanding of the properties of this family of eminently castable engineering materials.

A second part to this report, 'Cast irons Part 2: Welding (ISO/CD TR 10809-2)' is now at a draft stage.

For more information about international standards for cast materials contact: Dr Pam Murrell at ICME, Tel: +44 (0) 121 601 6976, email: pam@icme.org.uk