J. S. Afr. Inst. Min. Metall., vol. 91, no. 12.
Dec.1991. pp. 435–439.

The manufacture of stainless clad steels

by W.A.H. POPPMEIER* AND J.C. VREUGDENBURG†

SYNOPSIS

An overview of methods of manufacture is presented, as well as the results of laboratory experiments on the making of stainless clad steels.

It is concluded that stainless clad steel can be made in South Africa with existing rolling equipment, and that good bonding between the two materials depends on clean mating surfaces, proper edge welding, and a minimum reduction of 25 per cent at a rolling temperature of 1200°C. In practice, a minimum reduction of 70 per cent at 1100°C is recommended.

Suggested applications for clad steel include parts and equipment for the chemical, petrochemical, marine-engineering, and mining industries, for the building sector,and for household appliances.

SAMEVATTING

'n Oorsig oor die vervaardigingsmetodes asook die resultate van laboratoriumeksperimente in verband met die vervaardiging van roesvry beklede staal word gegee.

Die slotsom is dat roesvry beklede staal met die bestaande walstoerusting in Suid-Afrika vervaardig kan word en dat goeie verbinding tussen die twee materiale afhang van skoon pasoppervlakke, behoorlike randsweising, en 'n minimum reduksie van 25 persent by 'n walstemperatuur van 1200 °C. In die praktyk word 'n minimum reduksie van 70 persent by 1100 °C aanbeveel.

Bekledestaal kan onder andere gebruik word vir onderdele en toerusting vir die chemiese, petrochemiese, skeepsingenieurs- en mynbedryf, in die boubedryf, en ook vir huishoudelike toestelle.

Introduction

Metal composites, which have been used since ancient times for ornaments and weaponry, are bonded laminates of two or more metals in which the clad layer exceeds 3 per cent of the total mass. Research into the industrial manufacture of clad steels started in the 1930s, but it took a further two-and-a-half decades before production commenced on an appreciable scale.

One of the advantages of composites is that they combine the prominent properties of different materials—such as the good corrosion resistance of stainless steels, and the higher yield strength and heat conductivity of carbon steels below 600°C. However, the main reason for the making of clad steels is the potential they offer for cost saving, since a portion of the expensive component is replaced by carbon steel. At present, the price ratio of SAE 304 stainless steel to BS 4360 43A is about 5:1. The ratio depends largely on the nickel price, which can fluctuate substantially.

The most widely used steel-base composite is low-carbon steel plated with stainless steel or titanium. On a smaller scale, aluminium, copper, and copper alloys are used as cladding materials. For purposes other than protection against corrosion, tool steels are combined with mild steel and are rolled into flat bars. The intermediate product is used in the manufacture of cutting tools such as shear blades.

The following are the methods that are most commonly used for the manufacture of metal composites.

- Batch or continuous processes are used for the spraying or casting of liquid metal onto a solid substrate.
- A partitioning plate is placed in a mould, and the base metal is poured into the larger compartment. After this section has partly solidified, the partition is removed, and the cladding material is poured into the remaining opening.
- A component is coated by an electro-slag remelting (ESR) process. The most common application is for the building up of wear-resisting material onto rolls made from less expensive steel. The roll is placed in the centre of a water-cooled mould, and the gap is filled by the remelting of the tube being used as the electrode. This is illustrated schematically in Fig. 1.
- The components are welded together by diffusion bonding, which involves the simultaneous application of pressure and heat.
- The components are heated, and are then bonded together by the application of pressure during rolling. This is called roll bonding. It is the most widely used method for the manufacture of clad steels.

Stainless clad steel finds its main applications in the chemical and petrochemical industries, in salt-water desalination plants, and in household appliances. The composites combine good strength with good corrosion resistance, formability, and weldability. They are used where the design specifies—for greater strength—a greater thickness than that required for protection against corrosion.

In Japan, plates that are over 5 m wide and over 100 mm thick are being manufactured. The minimum sheet thickness is about 3 mm, the layer of the cladding material being typically between 5 and 20 per cent of the total thickness. Cladding can be applied to both surfaces of a

* Process Metallurgy, Research and Development, Iscor Limited, P.O. Box 450, Pretoria, 0001.

ISSN 0038-223X/3.00+0.00. Paper received 9th July, 1990; modified paper received 29th January, 1991.

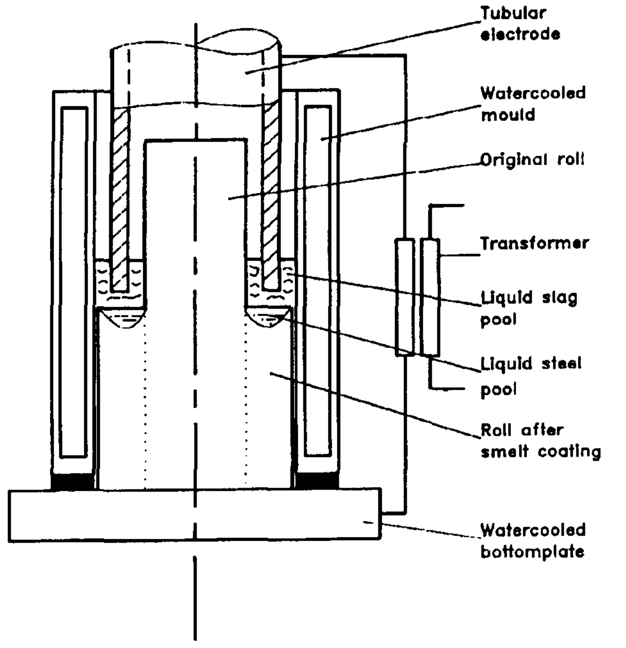


Fig. 1—Building up of a roll by the electro-slag remelting process

base plate, but the 'open-sandwich' arrangement is that used most often.

Cladded bars and profiles are also being manufactured. About three years ago, tests were conducted on the production of stainless clad bars at Krugersdorp. The company concerned later continued the trials in England[1]. No stainless clad steels are being manufactured in South Africa at present.

Overview of the Manufacture of Stainless Clad Steel[2–9]

The steps in the manufacture of flat clad-steel products are shown in Fig. 2.

Selection of Dimensions

The selection of the thickness of the two components before processing depends upon the specified cladding ratio. Because of their different strengths, the two materials deform differently during rolling. For example, stainless steel has a higher resistance to deformation at rolling temperature than does carbon steel. The reduction in thickness is therefore less for the alloyed steel.

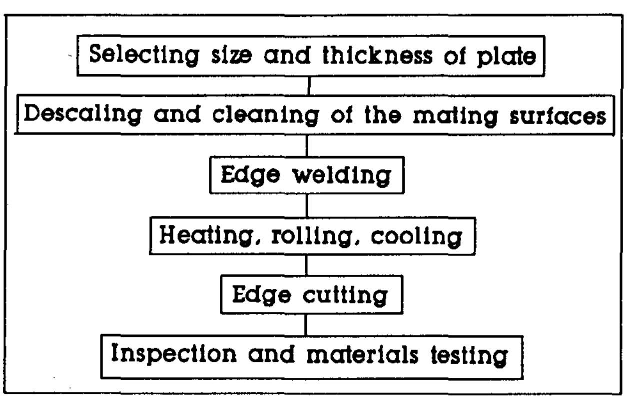


Fig. 2—Flowsheet for the manufacture of flat products

Descaling

Two main methods are used for cleaning the mating surfaces: pickling in acid, and abrasive shot blasting. On occasion, the surfaces are machined.

Mechanical descaling has the advantage that it does not lead to intergranular attack, pitting, hydrogen embrittlement, or cracking. The disadvantages of mechanical descaling are its high cost, as compared with that of chemical cleaning, and the possibility that it may obscure surface defects. Clean, previously unused glass beads, iron-free silica, or alumina sand are recommended for use in the abrasive blasting of stainless steel, after which the steel should be dipped briefly in acid. However, the possibility that residual metal oxides may become embedded during the blasting process cannot be totally excluded.

Surfaces that are free of scale, foreign particles, and gases are obtained by explosive forming. This process is used at various places to clean and prebond the materials prior to rolling. Cleaning and joining in vacuum is a very effective process, but is costly and unpractical for large plates.

Edge Welding

Edge welding of the 'sandwich' should be carried out with stainless-steel electrodes. A few small openings should be left to allow entrapped air and other gases to escape during heating and the first rolling pass. During the first few passes, the weld must be strong enough to withstand the shearing forces that prevail as a result of the different elongation tendencies of the two materials during forming.

Rolling

Heating of the metal to rolling temperature must be slow up to 800°C because of the low heat conductivity of stainless steels up to that temperature. The temperature of the materials at the start of rolling is from 1100 to 1200°C.

The recommended end-temperature for the rolling of austenitic clad steels is around 900°C, but composites in which ferritic grades of steel are used can be finished at lower temperatures when a fine-grained structure is required.

The reduction per pass can vary over a wide range, and is dependent on the design of the rolling mill and the selected rolling temperature.

The main requirements for good bonding, apart from the quality of the mating surfaces, are the correct rolling temperature and reduction in thickness.

Heat Treatment

Heat treatment at 1050 to 1100°C, followed by rapid cooling, is applied to austenitic steels to improve their corrosion resistance, workability, and toughness. This treatment is not usually applied to composites, because excessive grain growth may occur in carbon steel at that temperature. A Japanese company claims that the properties of both steel components are excellent when the laminate is rapidly cooled from 900 to 500°C immediately after the last rolling pass[4].

Properties of the Product

Weldability, corrosion resistance, and formability have been extensively investigated by two Japanese companies that produce large tonnages of stainless clad steels[4,5]. They found that butt welding causes no problems in plates provided that certain procedures are applied. Fig. 3 gives an example of effective groove design. The welding of parts onto the surface of a composite requires some precautions if the bond in that area is not to be affected.

The corrosion resistance of austenitic stainless cladding is good, although the values for grain-boundary and pitting corrosion are slightly higher than those for heat-treated single plates of the same material.

The formability of properly bonded laminates is good, and dished ends for pressure vessels and kitchen pots can be manufactured from clad steel. A European company has also reported[2] good deep-drawability for stainless clad steel.

Experimental Procedures

For the trials on the making of stainless clad steels, a rolling mill with a rolling force of 100 t was employed. Samples were made from 200 by 50 mm plates. The thickness of the carbon-steel parts was between 10 and 20 mm, while that of the stainless-steel parts varied from 2 to 10 mm. In most of the experiments, plates of 10 mm thickness were used for both parts of the composite. Carbon steel to BS 4360 43A, and stainless steel to SAE 316L, were used.

In some trials, descaling was carried out by machining of the mating surfaces but, in most of the tests, the samples were sandblasted. The carbon steel was subjected only to abrasive blasting but, after sandblasting, the stainless-steel plates were cleaned briefly in acid.

Edge welding was carried out with a stainless-steel electrode on a flat plane, i.e. there were no V-grooves. The samples were heated in a muffle furnace at a rate of about 40 K per minute. The holding time at temperature was 30 minutes. The rolling temperatures were between 900 and 1200°C, and the reduction per pass varied from 8 to 30 per cent. The maximum total rolling reduction tested was 85 per cent. After being rolled, the samples were cooled in air. No heat treatment was applied.

The bonding strength of the composites was determined on test pieces (Fig. 4), which were pulled on a standard tensile test machine.

Bend testing was used for qualitative evaluation of the bonding. In these tests, a sample was repeatedly bent and straightened by 90° over a radius that measured one-half

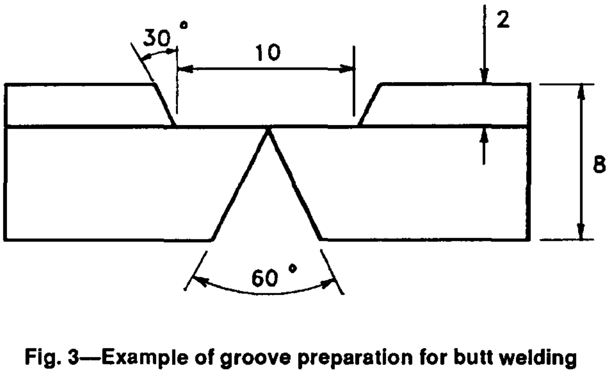


Fig. 3—Example of groove preparation for butt welding

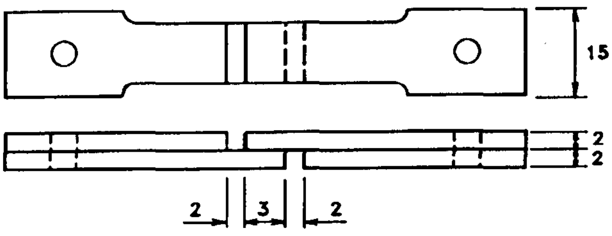


Fig. 4—Schematic representation of a sample used in the determination of bonding strength

of the thickness of the composite until the sample fractured.

No corrosion tests and systematic welding trials were conducted in the present work.

Experimental Results

Influence of Surface Quality on Bonding

It was established that treatment of the surfaces by sandblasting, followed by brief cleaning with acid, allows the specified bonding strength to be achieved with adequate rolling parameters.

Surfaces that had not been descaled did not bond up to the maximum investigated 85 per cent reduction at 1200°C. It was also found that samples with properly treated surfaces that had been kept for 24 hours without protection before edge welding did not bond at the maximum reduction.

Edge Welding

None of the samples showed rupturing of the welded edges during heating or rolling. The maximum reduction per pass was 30 per cent.

Reduction in Thickness

The results of the tests are presented in Fig. 5, which shows that the difference between the reduction in thickness of the two steels was less than had been calculated from their resistance to deformation. The reason for this behaviour is that independent elongation of the two plates was restricted by the welded edges, as well as by friction and bonding of the materials during rolling. The thickness of the two plates before rolling was 10 mm each.

Under specific rolling conditions, the resistance to deformation at 1200°C was 120 N/mm^2 for the stainless steel and 80 N/mm^2 for the carbon steel. The higher resistance to deformation of the stainless steel is due to its higher hot strength, and to the high degree of work-hardening during rolling as a result of the low rate of recrystallization, which is a typical feature of these steel grades.

Bonding

For bonding to occur, the array of atoms on the surfaces of the two materials must be brought within about an atomic diameter from one another, which is of the order of 3,5 Å. Surface films of iron oxide, which form immediately after the surfaces have been cleaned in air, i.e. not under inert gas, and which are a few hundred angstroms thick, initially prevent metal-to-metal contact.

However, during rolling, the plastic flow of the steel breaks up and disperses the oxides, allowing uncontaminated areas to come into contact and to produce a weld.

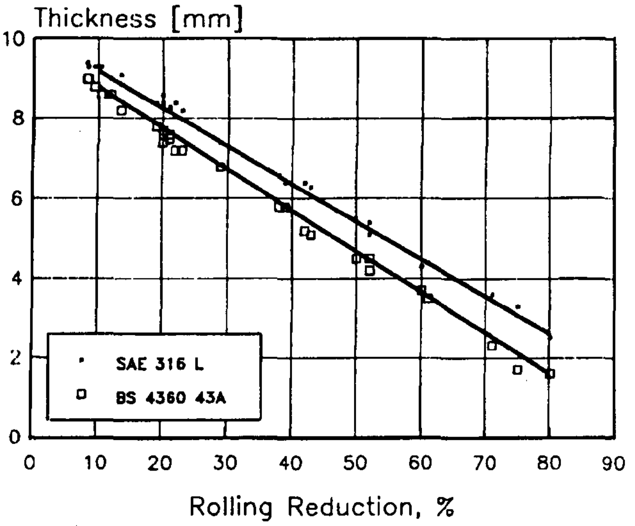
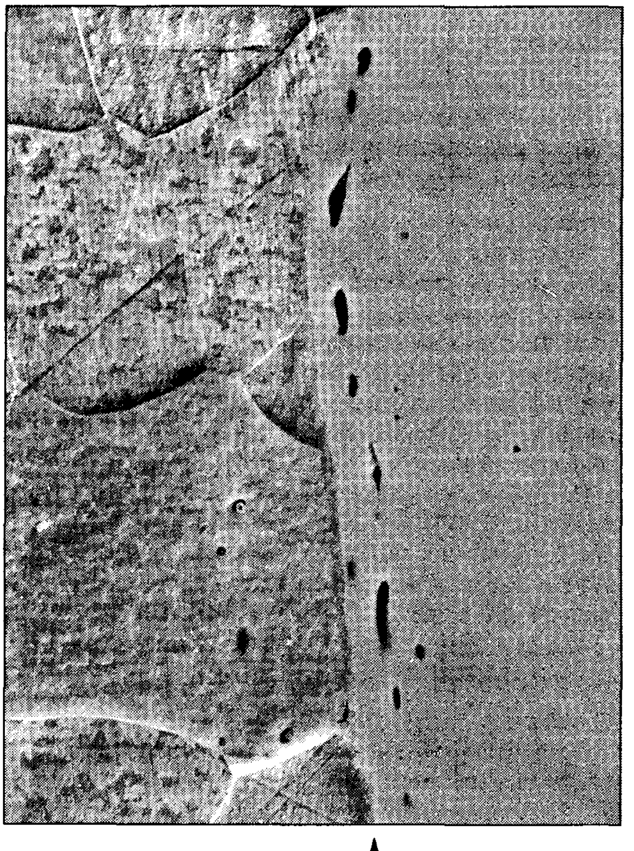


Fig. 5—Comparison of the reduction in thickness of carbon and stainless steels

Simultaneously, the oxides begin to dissolve in the base material. Fig 6. shows an interface in which the oxide film has been disrupted and dissolution of the oxides has been in progress. The photomicrograph shows a sample that was rolled at 1200 °C for a total reduction of 25 per cent in two passes.



carbon steel — former interface — stainless steel

Fig.6 —Dispersed and partly dissolved oxides in the former interface between a stainless and a carbon steel (SEM, original magnification 2000 X)

The dissolution of oxide films is significant in metals that have a relatively high solubility for oxygen. With increasing temperature, the solubility and mobility of the oxygen in iron increase considerably, promoting relatively rapid assimilation of the oxides by diffusion[10].

Migration of the elements also takes place during this period. Chromium and nickel diffuse from the stainless steel into the carbon steel. On a composite rolled in two passes at 1200 °C for a total reduction in thickness of 20 per cent, the concentration profiles of chromium, nickel, and iron at the interface were determined with a scanning electron microscope (SEM)[11]. The depth of penetration of the nickel into the carbon steel was about 10 μm and that of the chromium about 25 μm. Japanese investigations have shown that carbon can penetrate as deeply as 150 μm into stainless steel during rolling.

In order to limit the diffusion of elements, nickel foil can be placed between the two plates before edge welding. However, this arrangement is not commonly used for steel-to-steel laminates; it is rather used for titanium-clad steel in which the formation of brittle intermetallic phases must be restricted.

The recommended minimum reduction is typically 70 per cent, e.g. a reduction in the thickness of a laminate from 40 to 12 mm. The requirements for bonding are the correct combination of degree of reduction and rolling temperature.

Fig. 7 presents the results of an investigation into threshold deformation, i.e. the deformation at which bonding is first detected at various forming temperatures.

The strength of bonding for various degrees of forming was determined on composites rolled at 1200 °C. It was shown that the shear strength increased almost linearly from 290 N/mm² at a reduction of 25 per cent to 390 N/mm² at a reduction of 70 per cent. These values were well above the minimum shear strength of 20 000 lbf/in²

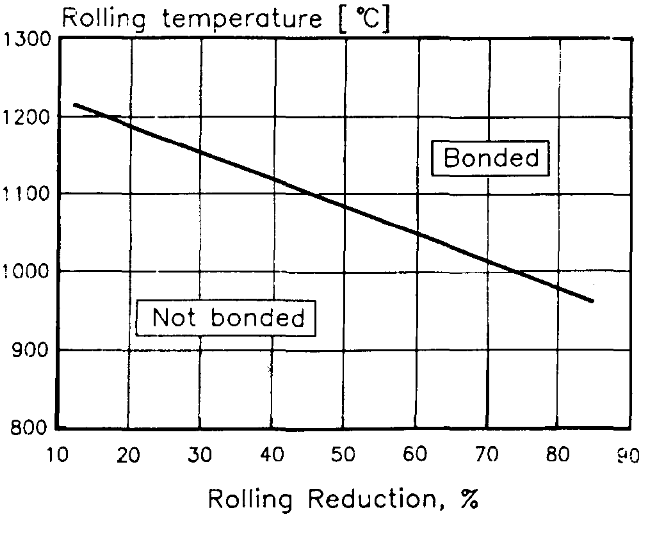


Fig. 7 —Threshold deformation in relation to rolling temperature

(140 N/mm^2), as specified by the American Society for Testing and Materials[12].

Conclusions

The results of experiments conducted in the laboratory employing, *inter alia*, a rolling mill with a rolling force of 100 t were in good agreement with data in the literature.

It can be concluded that stainless clad steel can be made with existing rolling equipment. Good bonding between the two materials requires clean mating surfaces, proper edge welding, and a minimum reduction of 25 per cent at a rolling temperature of 1200°C. In practice, a minimum reduction of 70 per cent at 1100 °C is recommended.

Stainless clad steels offer cost savings over solid stainless steel. The magnitude of the saving depends on a large number of factors including the nickel price, which has fluctuated widely in the past few years.

Clad steels can be used in the chemical and petrochemical industries for components that are to be resistant to corrosion by salt water, in the building sector, and in household appliances. They could also have a high potential in the mining industry, where not only corrosion-resistant materials but possibly also other combinations of steels could be applied successfully.

References

1. ANON. *Steel Times*, Sep. 1990. 506 pp.
2. O'DONNELL, R. Manufacture of acid resistant cladded steel sheet. *Neue Hütte*,. Sep. 1956. pp. 469-475. (In German.)
3. MATSUOKA, T., *et al.* Sumitomo clad plates. *The Sumitomo Search*, no. 27. Dec. 1982. pp. 37-43.
4. UEDA, H., *et al.* Explosive bonded and rolled clad steels. The Sumitomo Search, no. 27. Dec. 1982. pp. 59-77
5. MATSUMOTO, K., et al. Development of high quality stainless-clad steels and copper nickel alloy clad steels. Nippon Kokan, *Technical Report* no. 44. 1985. pp. 21-29.
6. YOSHIWARA, S., *et al.* Bonding condition of rolled titanium clad steel. *Tetsu-to-Hagane*,. 1986. pp. 137-143. (Translation from the Japanese.)
7. SUKONNIK, I. Clad metal technology in the U.S.S.R. *Met.*, Nov. 1986. pp. 44-46.
8. BLICKENSDERFER, R. Roll cladding in a vacuum. Advanced Materials & Processes Inc., *Metal Progress*, 4/88. 1988. pp. 47-49.
9. MASUDA, S., *et al.* Rolling characteristics of cladding plates in hot roll bonding process. *Trans. Iron Steel Inst. Jap.*, vol. 28. 1988. pp. 470-477.
10. SCHWARTZ, M.M. *Modern metal joining techniques*. New York, Wiley Interscience, 1969.
11. SMUTS, J., VON MOLTKE, T., and MYBURGH, H.A. Iscor Research, private communication, 1990.
12. AMERICAN SOCIETY FOR TESTING AND MATERIALS. Designation A263-84a, A 264-84a, A 265-84. May 1985. pp. 96-124.

IMM awards

Given below are details of the trust funds, etc., to which applications are invited for grants, etc., payable in 1992. Application forms, which must be returned to the Secretary before 15th March, 1992, are available on request. Applicants should note that, in general, preference will be given to members of the Institution.

Bosworth Smith Trust Fund

Approximately £3000 will be available in 1992 for grants from the Bosworth Smith Trust Fund for the assistance of post-graduate research in metal mining, non-ferrous extraction metallurgy, or mineral dressing. Applications will be considered for grants towards working expenses, the cost of visits to mines and plants in connection with such research, and purchase of apparatus.

G. Vernon Hobson Bequest

Applications are invited from the income of the G. Vernon Hobson Bequest, established for the 'advancement of teaching and practice of geology as applied to mining'. It is expected that approximately £3000 will be available in 1992. One or more awards may be made for travel, research, or other objects in accordance with the terms of the Bequest.

Stanley Elmore Fellowships

Applications are invited for Stanley Elmore Fellowships, which are awarded by the Institution and tenable at United Kingdom universities, for research into all branches of extractive metallurgy and mineral processing. Fellowships to a value of some £10 000 per annum will be available from October 1992.

Edgar Pam Fellowship

The Edgar Pam Fellowship will be awarded in October 1992 for post-graduate study in subjects within the Institution's fields of interest, which range from exploration geology to extractive metallurgy. Those eligible for the award are young graduates, domiciled in Australia, Canada, New Zealand, South Africa, and the United Kingdom, who wish to undertake advanced study or research in the United Kingdom. The maximum value of the Fellowship, which is tenable for one year, will be £4000.

Conditions for the Awards

Applicants for IMM awards must ensure that the particular fund from which support is being sought is relevant to their field(s) of interest. Applications that do not meet the terms and conditions of any field(s) and those which are received by the secretary **after** 15th March, 1992, will not be considered by the Awards and Grants Committee. Equally, applications for which the appropriate letters of support have not been received by 15th March, 1992, will not be submitted to the Committee.

Application forms for the Institution awards may be obtained from

The Secretary
The Institution of Mining and Metallurgy
44 Portland Place
London W1N 4BR
England.