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An Overview of The Commercialisation of The Spray Forming Process

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INTRODUCTION

The metallurgical advantages derived by the spray forming of molten alloys into semifinished product shapes have been extensively documented. These advantages arise from the rapid solidification of gas-atomized molten droplets during flight, and on deposition, in an inert gas environment. In brief, the resulting semi-finished products are characterized by: - (i) macro-segregation free microstructures; (ii) fine, uniform, equiaxed grain structures; (iii) fine, primary phase precipitates; (iv) oxygen contents; and (v) enhanced hot workability. Consequently, the properties of cast or wrought alloys are often improved and those of P/M alloys duplicated by means of spray forming. Furthermore, new alloys, metal matrix composites, in-situ reactive alloys, materials for thixoforming and clad products have all been developed and reported in the literature.

However, the metallurgical benefits can only be realized commercially if such products can compete in the market place. In this respect, the main attraction of spray forming is the single-step operation from molten alloy to a consolidated, spray formed product. Such a single-step implies low capital costs (less equipment required), low operating costs (low energy consumption and high material yields), and low overhead costs (less stock and work-in-progress with shorter delivery times).

Unfortunately, a single-step operation was not sufficient to guarantee success for spray forming, and significant advances were required in order to compete with conventional routes of manufacture (e.g. ingot casting/forging/rolling, VIM/ESR/forging etc.) where technology is established and production volumes are large. Consequently, in recent years significant efforts have been directed at both technical improvement and cost reduction programs. In particular, it has been necessary to: - (i) maximize plant throughputs (e.g. larger melt and spray-form sizes, higher deposition rates, and increased productivity); and (ii) to improve process efficiency (e.g. lower gas consumption, higher deposition yields and improved dimensional control) for various products.

The results of these efforts are briefly reported below.

ROLLS

The first commercialization of spray forming was in Japan by Sumitomo Heavy Industries Foundry and Forging Company which has been manufacturing spray formed rings in high Cr cast irons and high C high speed steels for several years. After downstream processing, the rings are fitted to a roll mandrel for use in round bar, flat bar, wire rod and section mills, mainly in finishing or intermediate stands. The main advantage such products offer is a fine, rapidly solidified carbide microstructure leading to improved thermal fatigue resistance and consequently longer roll lives, compared to conventionally cast products.

In recent years, there has also been considerable interest in the direct manufacture of large, clad

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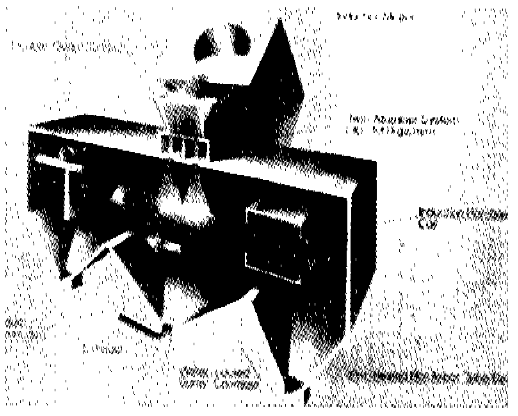

Fig. 1. Clad Products Concept

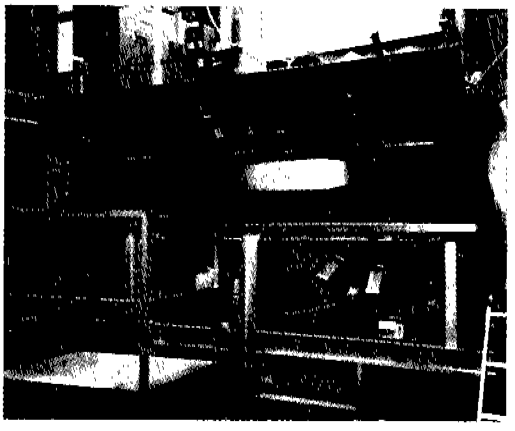

Fig. 2. Clad Roll-High Speed Steel Cladding Roll Arbor (Forged Rolls/ British Rollmakers

rolls, particularly for use in hot and cold strip mills. In this respect, a joint project is being carried out between Forged Rolls (UK) and British Rollmakers, (both members of the Sheffield Forgemasters Group), Sheffield University and Osprey Metals, with part-funding by the UK Dept. of Trade and Industry. Following the scale-up of an existing plant at Osprey it is now feasible to clad roll arbors up 400 mm in diameter × 1 m long; the concept is shown in Fig. 1 and a typical clad roll in Fig. 2.

Initial trials have concentrated on cladding with conventional cold mill roll alloys (e.g. 0.8C/3Cr, 0.8C/5Cr and 1.6C/11Cr) and hot mill alloys (e.g. 2.5C/17Cr and high speed steels). The first results were recently presented by Forged Rolls at an Institute of Materials "ROLLS 2000" Conference, where it was concluded that: -

- for cold mill alloys, the scale of the spray formed microstructure is comparable with that of conventional materials which have undergone heavy forging, except for an absence of very coarse carbides in the sprayed microstructures;
- for hot mill alloys, the spray formed microstructures are significantly refined compared with conventionally cast roll alloys, with all coarse eutectic carbides being eliminated;
- a high integrity, metallurgical bond is formed at the arbor/spray deposit interface.

The most significant step forward in the manufacture of clad rolls has been the development of the metallurgical bond using a roll arbor preheating device in conjunction with multi-atomizers.

Currently, work rolls are being produced for testing in cold and hot, narrow, strip mills. If this proves successful, it is envisaged that a larger plant would be installed

at Forged Rolls/British Rollmakers to spray form clad rolls up to approximately 800 mm dia. × 2 m barrel length.

A similar project is planned between Babcock & Wilcox and National Roll in the USA, where the major emphasis will be on the manufacture of hot strip mill rolls clad with high speed steel.

STAIM, ESS STEEL TUBING/CLAD TUBING

Using their 1 ton capacity plant in Sweden, Sandvik can produce stainless steel tubes up to 400 mm diameter × 50 mm wall thickness × 8 m long. However, one of the major technical problems encountered has been the occurrence of porosity (e.g. up to 2-5 mm depth) in the internal bore of the spray formed tube, corresponding to the initially deposited metal being excessively cooled by the cold collector tube. Such porosity leads to considerable loss in material yield and therefore increased manufacturing costs for its removal. Fortunately, a solution to this problem has recently been effected by the use of multi-atomizers and other special techniques. These improvements together with a scale up in melt capacity to 4.5 ton on a new plant installed by Babcock & Wilcox (under a US Navy Mantech program) offer the possibility of considerably lower cost manufacturing for large diameter stainless and nickel alloy tubing. However, the most interesting market appears to be for the manufacture of bimetallic tubing with a corrosion resistant layer being sprayed onto the outside of a collector mandrel for applications in boilers, incinerators and waste heat recovery plants. In this respect, Sandvik have developed a new, highly corrosion resistant alloy (Sanicro 65) by means of spray forming, for service as evaporator and superheater materials in waste incinerators.

SUPERALLOY RINGS AND BILLETS

Howmet (USA) are operating a pilot plant for the spray forming of superalloy ring blanks up to 800 mm dia. × 500 mm long. In a recent joint publication by Rolls Royce, Howmet and Ladish, (EPMA Conference Proceedings, Oct 1995) it was stated that "the new generation of large, high thrust engines are leading to more demanding/requirements for ring/casing components. These increasing requirements will potentially' lead to the use of highly alloyed/high strength materials.

These materials are inherently more costly and difficult to process. The article also states "the Howmet Spraycast X™ process has been identified as a potential, low cost, manufacturing route for high strength, nickel-based superalloys for ring/casing components". Based on a study on Udimet 720, the article concludes: -

- the Spraycast-X™ process has been demonstrated as a feasible manufacturing route for ring preforms in high strength materials;
- the ring preforms have been successfully processed by ring rolling or hipping;
- a uniform, equiaxed microstructure was generated with minimal variation throughout the section thickness;
- porosity was evident in the as sprayed preforms but subsequent processing of the preforms manufactured by the "single pass" technique resulted in full densification. This was not the case with the "multi-pass" technique which showed retained porosity;
- the mechanical properties of the rings evaluated were shown to be comparable, or better than, the cast and wrought standard of material.

Howmet are currently operating a 1000lb capacity plant and it is likely that further scale-up will be required if sufficiently low cost manufacturing is to be achieved.

An interesting choice which has to be addressed in the near future for any manufacturers of spray formed rings will be the mode of operation of a full-scale manufacturing unit. Should rings be manufactured using a large capacity tube plant, whereby tubes in several standard sizes are sectioned and subsequently ring-rolled? Alternatively, should rings be spray formed on an individual basis for either hipping and/or ring rolling? The former route offers the potential of the economics of scale and the possibility of competing in the existing ring market for conventional superalloys whilst, at the same time, producing the new high strength alloys. The latter offers the possibility of pre-shaping rings and improving material yields, which could be a major advantage for the new alloys, although markets could initially be small until the new generation of jet engines are widely established.

These high strength superalloys are also required for turbine-discs where cleanliness is of critical importance if acceptable low cycle fatigue properties are to be generated. The main route of manufacture of conventional disc alloys involves triple melt (i.e. VIM-to produce the basic composition, ESR-to remove inclusions, VAR-to improve microstructure) followed by heavy deformation and forging. However, this route cannot be applied to many of the high strength superalloys, due to microstructural and related hot-workability problems. For these alloys, the powder metallurgy route is normally used, which typically entails: VIM (to produce basic composition), VIM plus atomization (to produce powder), sieving (to produce fine powder and remove large inclusions), canning and hot isostatic pressing or extrusion (to consolidate the powder) and forging (tb produce the final shape).

Whilst the spray forming process has always offered potential economic attractions due to the low number of process operations, until recently, there has been no method of achieving the necessary level of cleanliness in a spray formed product. However, a new process invented by GE (US Patent No. 5,160,532) offers a solution to this problem.

The new process termed "ECS" (Fig. 3) combines ESR (electro-slag remelting) with CIG (cold-walled induction guide) and spray forming. A VIM electrode is re-melted in an ESR furnace where the liquid slag dissolves any ceramic inclusions. Instead of withdrawing a cast billet from the base of the furnace (as with the normal ESR process) a controlled stream of clean, molten alloy is conducted from the base of the unit, via a water cooled, copper funnel with induction heating (i.e. a CIG nozzle, which has been developed by ALD, Germany) into a spray forming unit, so that a fine-grained, segregation-free billet can be manufactured.

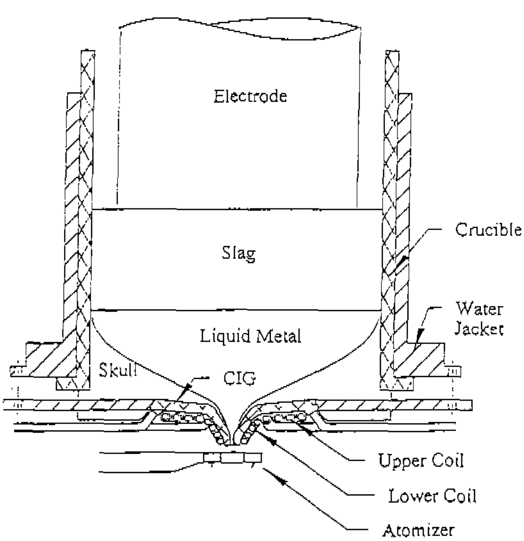

Fig. 3. ECS Process (GE. USA).

In co-operation with Teledyne Allvac, ALD and Osprey Metals, a large pilot plant has been constructed and is under operation at GE to demonstrate the technical and economic viability of the ECS Process. Billets in alloys such as Rene 95, Rene 88 and IN718 have already been spray formed up to 500 kg in weight and are under extensive evaluation with respect to cleanliness, microstructure and hot workability.

HIGH ALLOY STEEL BILLETS

Round billets are normally produced in either "vertical" or "horizontal" (Fig. 4) spray forming plants. Essentially the two techniques are similar except for the collector movement which is either in a vertical or horizontal direction. The vertical concept is currently used on aluminum and copper alloy billet plants (see later) whilst the horizontal concept is being used at Osprey Metals for processing high alloy steels. Initially, the plant at Osprey was limited to a melt capacity of 300 kg and a billet diameter of 200 mm but under a joint project with Danish Steel, Special Melted Products and Mannesmann-Demag (partly funded by the European Coal and Steel Commission) the plant has been scaled up to a 1.2 ton melt size. Using this plant,

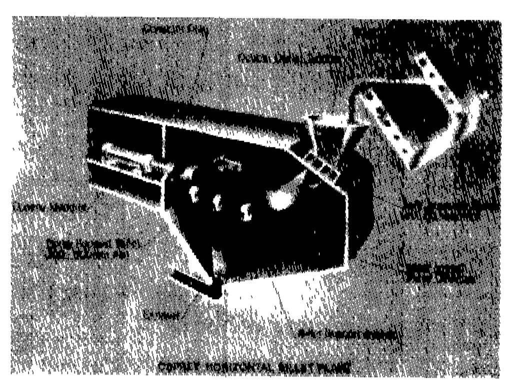
Fig. 4. Billet Production (Horizontal Mode).

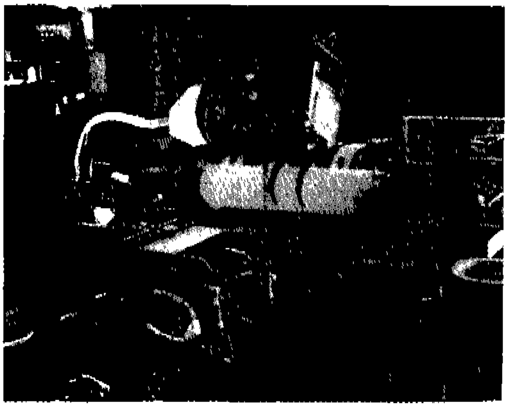

Fig. 5. Spray-Formed Tool Steel Billet (SMP/DDS).

steel billets have been spray formed at 250, 325 and 400mm diameter up to 1.2 m long (Fig. 5) in both tool steels and precipitation hardening stainless steels. As a result of rapid solidification, initial results on these alloys have been completely satisfactory and, most encouragingly, the cost of spray forming has been demonstrated to be greatly reduced.

This is mainly due to the use of a twin-atomizer, rather than a single atomizer arrangement. The benefits of using this system, include: -

- the ability to manufacture billets up to 400 mm diameter (therefore increasing plant throughput and extending the range of potential products);
- a 100% increase in metal dispensing rates (and, therefore, production rates) up to approximately 55kg/min, depending on alloy composition;
- a 25% reduction in nitrogen atomizing gas consumption to about 0.75 Nm^3/kg of metal atomized; and
- an increase in deposition yields from about 70% to in excess of 90% (for 325 mm dia. billets).

With such improved performance, it is considered that the spray forming route with its single step from molten alloy to a spray formed billet (immediately available for forging) could be cost competitive with conventional ingot casting routes for high alloy steels (e.g. tool steels, die steels, high speed steels etc.). The superior microstructures which are realized also make spray forming an attractive route as a replacement for Consumable Electrode Re-Melting, for certain applications.

ALUMIMUM EXTRUSION BILLETS

Aluminum alloy billets are manufactured by the "vertical" technique. Substantial quantities of billets in hyper-eutectic A120Si type alloys have been produced for subsequent extrusion and forging into final products at both PEAK (Germany) and Sumitomo Light Metals (Japan). The current plants are restricted to spray forming billets with diameters of 250-400 mm by 1-1.4 m long. However, new plants are expected to be constructed in the near future in which the billet length will be approximately doubled and plant output on a single shift basis will be about 1,000 tpa. Using a specially developed control system the dimensional tolerance achieved on existing billets is approximately+2 mm at 250 mm diameter, which enables direct extrusion of the billets without machining.

The largest potential market for spray-formed Al/Si components is in the automotive field (e.g. pistons, con-rods, etc.) where weight savings compared to cast Al/Si components (in which alloy composition and therefore strength is limited due to segregation) can lead to improved engine efficiency and reduced vibration.

Other aluminum alloys are also at an advanced development stage and include: - (i) high strength Al/Zn alloys (with 700-800 MPa UTS in conjunction with high fatigue and fracture toughness levels); (ii) ultra low density Al/Li alloys (with Li contents up to 4%) and (iii) low coefficient of expansion Al/Si/X alloys with expansion values at any desired level in the range 6-14 ppm. The Al/Si/X alloys are being developed by Osprey Metals in conjunction with GEC, Alcatel Espace and TNO under an EC Brite Project for applications in the electronics packaging field.

Further development of aluminum alloys will be carried out at Penn State University Advanced Research Laboratories (USA) which has recently acquired an R and D plant for such purposes.

COPPER ALLOY BILLETS

Two pilot plants are in operation at Wieland (Germany) and Swissmetal (Switzerland) for the spray forming of copper alloy billets up to 300 mm dia × 2.2 m long. These plants have mainly being used for alloy development purposes and production has been limited whilst markets are developed for the new alloys.

Alloy development programs have included: - on (i) Cu15Ni8Sn where high strengths in combination with reasonable levels of electrical conductivity can be achieved; such an alloy could replace Cu/Be for applications such as connectors or springs; (ii) Cu bronzes with elevated Sn content where spray forming can improve hot and cold workability and provide material with high strength levels, also for possible use in springs; (iii) CuCrZr where spray formed material fabricated into welding electrodes gives longer lives than electrodes from continuously cast alloy; and (iv) copper alloys containing injected graphite particulate for a range of applications (e.g. to improve the wear properties of sliding rails).

RESEARCH AND DEVELOPMENT

A national network of R&D spray forming plants are gradually being established Worldwide (e.g. Drexel University (USA), US Navy (USA), Penn State ARL (USA), RIST (Korea), Bremen Institute (Germany), National Cheng Kung University (Taiwan) etc.). These plants are particularly useful for developing new materials (i.e. new alloy compositions, MMCs, reactive alloys, clad products and materials for thixoforming) as this is a major advantage which spray forming technology offers. Moreover, as a result of the gradual commercialization of spray forming technology for existing alloys, it should be relatively easy in the future to introduce these new materials into pre-existing, low cost manufacturing equipment.

SUMMARY

(i) The development of a metallurgical bond during the spray forming of clad products has offered the possibility of manufacturing large rolls, including those used in hot and cold strip mills. Small rolls are already being produced in Japan.

(ii) Technical developments, including the use-of-multi-atomizers have resulted in the elimination of porosity from the internal bore of a sprayed tube. Bimetallic tubing can also be manufactured and the installation of a 4.5 ton tube plant in the USA should provide low operating costs.

(iii) Spray forming offers a potentially low cost manufacturing route for superalloy ring/casing components in high strength superalloys.

(iv) A large pilot plant has been built for the spray forming of ultra-clean superalloys for turbine disc applications.

(v) Using twin-atomizing technology, special steel billets have been spray formed up to 400 mm diameter with deposition yields in excess of 90%.

(vi) Al/Si alloy extrusion billets with excellent dimensional tolerances are being manufactured for large scale automotive applications. Several new aluminum alloys have also been developed, including high strength, low density and low coefficient of expansion materials.

(vii) New copper alloys have been developed and pilot plants are in operation to produce these alloys once markets have become established.