HIPing brings new horizons for casting manufacturers

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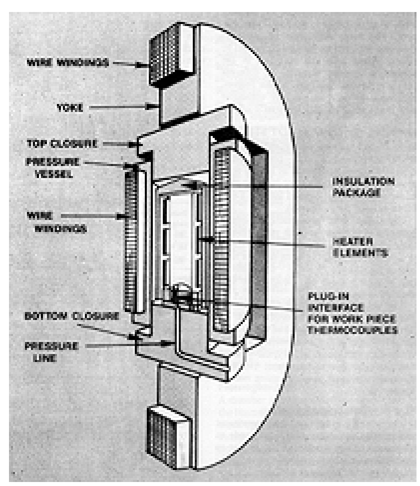
The application of Hot Isostatic Processing to the removal of porosity from castings has been recognised for many years. However, technical data associated with the improved properties following HIP treatment are only now receiving more widespread distribution. In order to devdop a better understanding of such improvements a series of trials has been conducted in conjunction with investment foundries. Using these results as a base, this paper summarises the available evidence to demonstrate that the exposure of castings to HIP treatments can develop properties equal to those expected from wrought materials.

During the last five years, continued interest has been focussed upon the reduction of manufacturing costs, and new technologies have been extensively reviewed to evaluate their potential role. All sectors of metal manufacturing have reappraised the possible application of powder metallurgy techniques, particularly those employing rapid solid fication methods. However, the introduction of such product routes has been slow.

Few would argue that the success of any competitive process depends upon the performance ofthe final product. Anv modification to the method of manufacture is at the discretion of the designer who measures the suitability of a part by the physical and mechanical properties it displays. The knowledge of mechanical properties is therefore fundamental to choice.

The present paper describes a short programme of work designed to show how properties typical of forged products can be attained using castings which have been subject to Hot Isostatic Processing (HIPping).



Hot Isostatic Processing is emerging rapidly as a production tool appropriate to a wide range of material technologies where improved performance is the ultimate objective. HIP processing involves the application of high pressure argon gas, within a strictly controlled thermal envelope, fig1. No pressing dies are involved since the combination of temperature and isostatic gas pressure pro vices those conditions whereby internal flaws, defects or pores collapse and are removed. As an example of the consolidation power available through HIP, fig 2 illustrates the way in which large odds may be removed from cast steel.

Fig 1 Cutaway view of an ASEA hot isostatic press. Components to be processed are placed within the central core and enclosed within the heater/insulation
package. (Courtesy of ASEA Limited)

Clearly the scale of void closure in fig 2 is deliberately impressive and such defects are rare in premium quality castings. The same cast pans do, however, suffer from micro cavitation arising from shrinkage effects during the liquid/solid transition. It is these micro-defects (fig 3) which although not resolved by macro X-ray techniques contribute to the marked reduction in cast-part performance when compared with fotged properties.

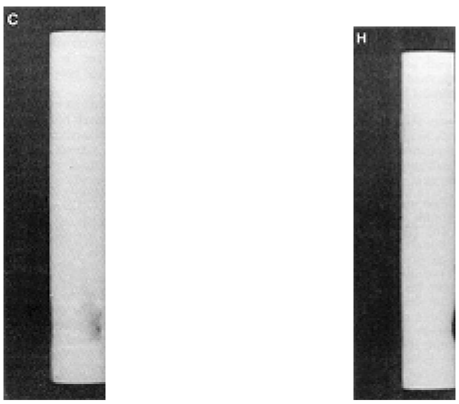


Fig 2a Radiographs showing the effect of HIP upon macro-sized voids within carbon stell san-cast test bar.
C - As cast; H - Cast + HIP. (Mag X0.25)

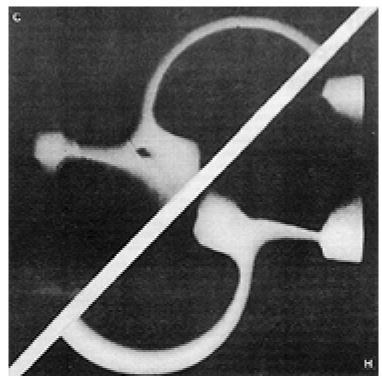


Fig 2b Radiographs showing the effect of HIP upon macro-sized voids within a sand-cast carbon steel valve body.
C - As cast; H - Cast + HIP. (Mag X0.3)

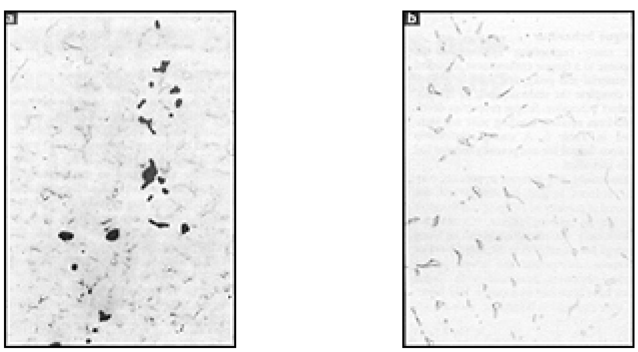


Fig 3a Investment-cast niobium-stablished 316 stainless steel
a) As - cast condition
b) Cast + HIP. (Mag X150).
Notice removal of porosity with little change in microstructure following HIP treatment.

CARBON AND ALLOY STEELS

Many workers have reported the influence and benefit of HIPping on the fatigue behaviour of highly alloyed superalloys. Recent work by Strodei, however, has demonstrated that this behaviour is not restricted to exotic alloys and that simple cast carbon steels can be substantially improved by such treatment (1100°C/120 mins/105 MPa). The fatigue limit of the cast product was improved by HIPping, to a point where it compared very favourably with similarly heat-treated longitudinal test pieces from rolled bar. Strode concluded that such an improvement was primarily the result of removal of microporosity. The removal of porosity and homogenisation effects arising during HIP treatment combined to remove the disparity of properties which could be identified when test pieces from different positions within a casting were compared. In addition, any attempt to simulate the homogenisation effects promoted by HIP by the use of a simple heat treatment was critically dependent upon the cooling characteristics of the test piece during solidification.

The effect of HIP on a cast case hardening steel has also been reponed2. This work illustrated the change in mechanical properties which could be expected following a HIP treatment and, more importantly, contrasted the data scatter with that from wrought products. In virtually aD aspects, the cast + HIPped component performed very satisfactorily in comparison to its forged counterpart. The large difference in standard deviation observed for the cast part could be closely linked with the variation in the volume % porosity achieved at different points within the cast bars. In this respect, their observations: are entirely consistent with those of Strode and Basaran et al3.

HIPPING OF LOW ALLOY STEELS

In the present work the properties typified by BS 817 M40 (formerly En 24 - comparable to AISI 4340) were considered as having wide application to the engineering industry and, as such, the base composition listed in Table 1 was isolated for evaluation.

Discussion with investment foundries indicated that those strength requirements demanded from the base composition could be satisfactorily achieved using cast and heat treated En 40B (BS 722 M24 - see Table 1), and as such a three part programme was outlined as noted below.

The range of alloys prepared within the study are noted in Table 2, together with En 24 type rolled bar manufactured via an electric arc - ingot rolling steelmaking practice. AD air-melt cast pieces were typical of those used for test bar measurement (15 mm diameter) and were prepared using normal foundry practice.

Part I - Process optimisation

Using previous work and heat treatment information, an initial study was made to determine the optimum HIP treatment to maximise mechanical properties. The results of this exercise are listed in Table 3. Clear evidence exists to demonstrate that elongation and impact properties have been markedly improved (see sub-table 3), and that a HIP temperature approaching 1150/ 1160°C successfully optimises performance. This trend was supported by other work conducted over a range of final strength levels.

Part 2 - Cast and wrought comparisons for En 40B

A further series of trials involving En 40B established the potential to approach wrought strength levels, using the optimised HIP treatment. The results are iDustrated in Table 4. It should be noted that, despite the inclusion of a normalise/anneal treatment to homogenise the as-cast test pieces, the overall effect of a HIP treatment is to improve elongation properties by some 30%. These results (Table 4) are further contrasted with typical data ffom wrought En 40B,which indicate that the range of properties offered by the cast product are somewhat limited. In contrast, the cast and HIPped En 40B parts allow equivalent property comparisons to be considered. During the programme of work evidence was obtained that the use of vacuum remelted feed stock for air meit castings also improves both elongation and impact pro perties. This is entirely reasonable in view of the reduction in the level of oxides, sulphides and residual elements (ie copper). However, the application of a HIP treatment to such alloys was still effective in further enhancing property levels, ie elongation was improved by an additional 15%.

Part 3 - Cast and wrought comparisons for En 24

Despite the potential interest in alternative cast specifications, the underlying conservatism within the engineering ffaternity often demands that any new part is produced in the same alloy as the one which it replaces. In order that this response could be anticipated, a series of trials was commissioned to examine the effect of HIP on air-cast En 24. Results from mechanical property comparisons are detailed in Table 5. The optimised HIP treatment used for En 40B was employed together with a final heat treatment schedule typically used for wrought products (oil quench - 830°C, temper 650°C). In addition, transverse sections from wrought bar (100 mm diameter) were included for comparison.

EFFECTS OF HIP - FURTHER ANALYSIS

Metallographic evidence from the cast test bars confirmed that the solid)fication morphology was predominantly columnar. Relatively little secondary dendrite coalescence and coarsening could be observed, which, together with the uniform distribution of interdendritic porosity, tended to suggest that solidification had been rapid and relatively constant in rate from edge to centre. Pores within the test pieces were of the order of 50 - 100 µm in size and were estimated to occupy 0.5 -1%, by volume. No porosity could be identified in any of the HIPped specimens, regardless of HlPping temperature.

Some evidence was observed that an ambient pressure normalising anneal tended to spherodise residual porosity but individual pores were not removed by such a treatment. Few additional microstructural differences could be detected between as-cast, cast and normalised and HIPped bars in the heat treated condition. All test pieces showed evidence of numerous two phase silicate and sulphide inclusions within the interdendritic networks.

Homogenisation

A number of references have been cited in the literature as to the influence of HIP treatment upon the segregation effects observed in cast materials. Extensive homogenisation brought about by HlPping cast structures in nickel-based superalloys has resulted in anoticeable improvement in their response to chemical machining. Similarly, an improvement in the conventional machining characteristics of cast precipitation hardening stainless steel has also been noted following HIPping.

To gain an understanding as to the extent of diffusion during HIP treatment of alloy steel, electron probe microanalysis results tor En 24 in the cast, HIPped and wrought condition are detailed in fig 4. The large difference in chemical homogeneity between cast and wrought product is not of itself surprising and the influence of an anneal/ normalising treatment would appear to be of only marginal benefit. By contrast, the effect of a HIP treatment at 1050°C is considerable and this results in segregation profiles identical to those observed from wrought products.

Fatigue behaviour

For many engineering applications the response to a fatigue environment is critical to material and processing route selection. To complete the understanding of HlPped product behaviour, fatigue properties developed from rotating bending tests are identified in Table 6. A strong relationship between fatigue life and porosity content has been identified.

Essentially, any increase in porosity content reduces fatigue capability, and the removal of porosity by HlPping can therefore provide far-reaching effects. Components traditionally manufactured from machined forgings are already being displaced by close tolerance castings and the fatigue performance objectives associated with forged stock have been met by a cast + HIP route. As with segregation behaviour, little advantage in fatigue performance is provided by a separate annealing treatment.

New horizons

Data from the present work appear to suggest that improved mechanical properties (particularly ductility, impact toughness and fatigue strength) in alloy steels can be achieved by the application of a HIP treatment. The present HIP study has not been exhaustite with regard to modification of HIP parameters. However, a temperature of 1050/1150°C appears effective in removing porosity from such materials. It may be argued that, since the works relating to the case hardening steel included HIP trials conducted at 1200°C, funkier improvements to the performance of En steels mav be possible. The potential risk of excessive grain growth should, however, be contrasted against anv additional improvement by exposure of castings to a still higher HIP temperature.

The results described relating to En 40B and En 24 confirm that HIPped castings can offer properties well in excess of those available from the cast and heat treated product. and equivalent to those specified trom wrought stock.

Importantly. such comparisons are supported bv other physical measurements, and it would not seem too speculative to suggest that such a route offers a significant challenge and an attractive alternative to conventional machining methods. Recent evidences has indicated that HIPped investment castings are already being used with great success and that major cost savings (30-40%) have been achieved.

Extrapolating such process methodology, research is already under way to assess the feasabiliry of achieving porosity removal and product improvement bv utilising standard heat treatment temperatures for the HIP parameters. In such a way it may be possible to achieve premium performance within the established and specified thermal practice for any steel specification.

It should be pointed out that the improvements described are not unique to ferrous based materials, and that similar trends have already been established for a wide range of metallic and non-metallic materials.

Table 1: Steel composition isolated for evaluation

	C	**SI**	**Mn**	**S**	**P**	**Ni**	**Cr**	**Mo**
Base compostition range (En 24)	0.35	0.1	0.45	.05 mx	.05 mx	1.3	0.9	0.2
(BS 817 M40)	0.45	0.35	0.7			1.8	1.4	0.35
En 40B	0.2	0.1	0.4	.05 mx	.05 mx	0.04 mx	2.9	0.4
(BS 722 M24)	0.3	0.15	0.65				3.5	0.7

Table 2: Actual compositions of test bars used within present study

Type	**Experimental trials***	**Cast or Wrought**	**C**	**SI**	**Mn**	**S**	**P**	**Ni**	**Cr**	**Mo**	**Cu**
En 40B	Part 1	C	0.28	0.39	0.43	0.019	0.028	0.28	3.3	0.52	
En 40B	Part 2	C	0.29	0.32	0.61	0.035	0.043	0.13	3.1	0.55	0.29
En 24	Part 3	C	0.4	0.35	0.63	0.035	0.040	0.58	1.21	0.29	0.27
En 24	Part 3	W	0.39	0.28	0.6	0.010	0.020	1.6	1.05	0.21	

Table 3: Optimisation of mechanical properties for cast En 40B using various HIP parameters

Condition	**0.2% proof (N/mm2)**	**UTS (N/mm2)**	**EI (%)**	**Izod (ft-lbs)**	**HB**
As cast + H.T.	953	1,071	8.9	10	220
HIP A + H.T.	927	1,058	12.1	16	223
HIP B + H.T.	945	1,073	13.8	17	220

Sub-table 3: Summary of improvements in elongation and impact properties

Condition		EI (%)	Izod
As cast + H.T. HIP A + H.T. HIP B + H.T.		0 +36% +55%	0 +60% +70%
- Results are averaged from three test bars per condition - Cast bar composition - see Table 2 - En 40B - Part 1. - Heat Treatment: -900° - 40 mins - oil quench / 610°C - 120 mins - air cool			
	Temperature (°C)	**Pressure (MPa)**	**Time (mins)**
HIP A* HIP B*	1050 1150	105 105	120 120