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Advantages of hot isostatic pressing (HIP) production routes for process manifolds

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SUMMARY

This paper considers conventional methods of manufacture of high pressure manifolds constructed in duplex and super duplex stainless steels. Details of manufacture of hot isostatically pressed manifold sections are presented. Improvements include the minimisation of welded joints and procedure qualifications and easier NDE interpretation. Fabrication and weld procedure qualification details are outlined and mechanical properties and corrosion resistance is discussed. Fracture toughness data is also presented. In conclusion the HIP manufacturing route for high pressure manifolds is compared with conventional methods of manufacture and significant technical and commercial advantages accrued by the HIP routes outlined.

INTRODUCTION

Conventional methods of manufacture of high pressure process manifolds in duplex stainless steels have employed 3 basic approaches.

a) pipe and butt weld outlets
b) extruded branches (including non standard tees)
c) swept outlets.

These methods are all labour intensive manufacturing routes requiring the manufacture of usually, non standard seamless or welded pipe of thick section. This then has to be forged or machined and prepared to accept the outlets or to form branches prior to manifold fabrication. As such, these routes can be associated with high costs and long lead times. Also when duplex and super duplex stainless steels are involved considerations of quality of fabrication, distortion due to residual stresses and ease of inspection and interpretation of NDE data can become problematical.

Many of these difficulties can be avoided if the technique of Hot Isostatic Pressing (HIP) is used for the manufacture of near net shape manifold sections with integral branches and branch connections (Fig 1).

This route provides a cost effective solution and a technically superior product which has now found application on several offshore developments. This paper compares and contrasts HIP with conventionally manufactured manifolds in duplex and super duplex stainless steels.

WHAT IS HIP AND HOW DOES IT RELATE TO DUPLEX/SUPER DUPLEX STAINLESS STEELS (D/SDSS) ?

The HIP Process

HIP is essentially three dimensional forging of a near nett shape dead mild steel canister which contains metal powder of the required chemistry. Metal powder is formed separately by a process known as atomisation. Two methods of atomisation are currently available, these are vertical and horizontal processes. Differences relate to orientation of the vessel and directional powder flow on gas impingement of the metal stream. Atomisation involves jet cooling with inert gas, a liquid metal stream of the required chemistry. The gas jets break up the liquid stream in to spherical particles which solidify rapidly to give chemically very homogeneous duplex stainless steel powder particles. Inert gas shrouding of these powders is maintained to minimise oxidation and fire hazard until they are stored in sealed stainless steel containers prior to use.

Canisters of hollow near nett shape manifold sections are manufactured by GTAW welding using simple and conventional sheet forming processes. These are filled with metal powder, sealed and leak tested prior to HIP'ing.

HIP'ing is carried out in a large autoclave where, for duplex stainless steels, pressures of 100 to 150 MPa and temperatures of 1100 - 1200°C are employed. During this cycle the powder particles yield and grain boundary creep and diffusion occurs giving rise to a linear shrinkage of approximately 10% and coalescence of powder particles to give a 100% densified product with no porosity. Examination of densification can be carried out using dye penetrant, ultrasonic, radiographic inspection and metallographic methods. Recently WML have supplied a HIP'ed Zeron 100 heat exchanger "D" shell which was prepared at one end to allow back face welding of exchanger tubes via pinnacle preparations. Subsequent radiography of the welded joint, tube and HIP tube plate pinnacle using highly sensitive Ytterbium isotopes showed no defects. The size of components which can be manufactured is limited to the confines of the autoclave. For manifold manufacture, the largest autoclaves must be used, currently the size of autoclave limits piece size to 3.1m in length and 1.1m in diameter.

Following HIP'ing, the product is heat treated and subsequently pickled or machined in order to remove the dead mild steel canister which encases a solid duplex stainless steel item. This process is shown systematically in Fig 2. For further details see references (1) and (2).

Properties of HIP D/SDSS

Tensile Properties

Typical tensile properties for D/SDSS are shown in Table 1.

Property	HIP Zeron 100 SDSS Typical	UNS S32760 Minimum Specified	HIP UNS S31803 DSS Typical	UNS S31803 Minimum Specified
UTS (MPa)	840	750	770	620
0.2% PS (MPa)	580	550	500	450
% EL	331	25	36	25
%RA	70	-	70	-
Hv_{10kg}	269	285 MAX	233	285 MAX

Table 1 - Typical Tensile Properties of HIP and Conventional D/SDSS

The properties achieved exceed common specification requirements. This trend is also true for elevated temperature tensile behaviour which for Zeron 100 SDSS is detailed in Fig 3. It is interesting to note that because the process is similar to three dimensional forging no texture is developed. Hence components are isotropic with no influence of sample orientation on mechanical properties, this is illustrated in Fig 4. Current design codes do not recognise this phenomenon or allow design engineers to take full advantage of this behaviour. Should codes change to recognise this effect then reductions in requirements for branch reinforcement may ensue.

Toughness

Generally, HIP D/SDSS can achieve 70 Joules average Charpy "V" notch impact test results at -10°C which is commensurate with a conventional forging. However, the form of the full impact energy vs temperature transition curve is quite different, since HIP items do not exhibit an impact transition temperature like conventional wrought products, Fig 5. In this case HIP products mirror the behaviour of D/SDSS weld metals, where the oxygen content lowers the upper shelf impact energy and extends its range to lower temperatures.

This impact transition behaviour of HIP D/SDSS is not currently recognised by design/fabrication codes which are all based upon the behaviour of wrought ferritic or austenitic steels. Hence codes call for high (upper shelf) levels of charpy toughness at minimum design temperature or below dependant upon the thickness compensation factor. The objective of this code requirement is to avoid brittle fracture and the impact transition region. This approach may not be relevant to D/SDSS and necessitates recourse to CTOD testing and calculation to establish minimum CTOD levels, measure actual CTOD and correlate this to a charpy "V" notch impact energy requirement which can be used for quality control purposes. An example of the usefulness of this approach is given by Mockler et al (3). Typical CTOD data and corresponding charpy results are given in Table 2.

Proc	Loc (1) Cap (2) Root	Temp (°C)	CVN (10 x 10) (J)			Ave	Lat. Exp (mm)			CTOD * (mm)			Ave
GTAW	WM(1)	-60	145	147	135	142	1.53	1.46	1.30				
	HAZ(1)	-60	146	144	145	145	1.43	1.51	1.51				
	WM(2)	-60	55	60	71	62	0.63	0.67	0.60				
	HAZ(2)	-60	96	60	71	76	0.96	0.54	0.60				
	WMC/L	-40								0.40	0.39	0.42	0.40
	WM1/4t	-40								0.31	0.42	0.40	0.37
	WM1/2t	-40								0.28	0.38	0.35	0.34
	WM3/4t	-40								0.33	0.31	0.34	0.33
GTAW/ SMAW	WM(1)	-20	40	35	38	38	0.41	0.45	0.45				
	FL(1)	-20	44	51	56	50	0.61	0.69	0.53				
	WM(2)	-20	33	33	32	33	0.36	0.34	0.39				
	FL(2)	-20	43	31	27	34	0.36	0.34	0.39				

Table 2 - Comparison of Charpy and CTOD results for weldments in HIP Zeron 100

* NOTES
1. CTOD specimens after BS 4515
2. Specification Requirements 55J Charpy impact @ -60°C after BS4515
3. Minimum CTOD for a defect size 5mm deep x 488mm long is 0.16mm after BS 4515 and PD 6493.
4. All CTOD measurements exceed the minimum requirement of 0.16mm therefore, weldments have sufficient structural integrity for this application with minimum design temperature of -40°C.

Whilst toughness of HIP D/SDSS is generally acceptable, this can deteriorate if oxygen contents exceed 200 ppm. For comparison, forged products would generally have oxygen contents of 60 ppm. It has been observed that HIP products made from powder formed by horizontal gas atomisation can have lower toughness (ie., 63-68 at -20°C), than products manufactured using powder produced in the vertical atomisation process (ie., 85-110J at -40°C) corresponding oxygen contents were 220ppm and 160ppm respectively. All other factors which influence toughness were equal. For this reason, where good low temperature toughness is required powder formed by vertical atomisation is preferred.

Corrosion

Corrosion tests on HIP Zeron 100 to ASTM G48 Method A show excellent performance with CPT of 80°C, while G48 Method B crevice corrosion test have CCT in excess of 55°C This good performance is probably due to the gas atomisation process which employs N_2 gas and gives rise to N_2 pick up in the liquid metal. Typical HIP SDSS N_2 contents are 0.26% compared to 0.22% for a conventional wrought product. For standard duplex grades typical HIP nitrogen contents are 0.2 compared to wrought product specification which calls for a minimum of 0.12 or 0.14%,

When considering sour service, NACE TM0177 cross welded tensile tests and autoclave corrosion tests show good performance. HIP D/SDSS also meet the hardness requirements of MR0175. However, NACE have recently declined to acknowledge HIP as an acceptable manufacturing process for products in duplex stainless steel alloys for sour service application. This is a clear anomaly as other HIP alloys are listed in MR0175. Moreover, as a general case MR0175 deals with alloy chemistry and heat treatment condition and with castings excepted, does not address the suitability of manufacturing routes per se In order to gain formal NACE approval it will be necessary to go through a full testing regime and obtain ballot item approval. Manufacturers in the USA intend to pursue NACE acceptance whilst European manufacturers will probably accept the more pragmatic approach to acceptance of materials for sour service offered by the European Federation of Corrosion.

Microstructure

The microstructures of HIP D/SDSS, Fig 6, shows an extremely fine grain size with equal proportions of austenite and ferrite. This is expected as a consequence of the rapid solidifications of the liquid metal stream during gas atomisation which following sieving, gives fine particle sizes of typically <350um. Also the solid state densification processes during HIPing occur at lower temperatures than the grain coarsening temperature for D/SDSS so fine grain sizes are maintained.

This contrasts with conventional wrought products where strong texture and anisotropic properties are observed. For thick components associated with high pressure applications grain sizes can be quite coarse as the degree of work put into the core of the component during manufacture can be small or contained mostly in the outer fibres of the product. This point is demonstrated by Cantini et al (4), where impact tests at -46°C for fusion line + 2mm and +5mm positions on extruded manifolds gives 120-130J in the 12mm case and only 50J in the 37mm thick case.

One other important factor associated with grain size is the influence on the degree of attenuation of ultrasonic waves. Coarse grains of austenite and ferrite make ultrasonic examination very difficult since poor signal to noise ratios are developed, this is especially true for castings. However, for fine grained powder products, ultrasound is not so highly attenuated and meaningful ultrasonic inspection of weldments becomes feasible (5). The net effect is that, for fabricated manifolds, the need for radiography which necessitates evacuation of the fabrication site for examination of installation welds is eliminated and more discerning and easier to employ ultrasonic examination techniques can be applied.

Fabrication

HIP D/SDSS are readily fabricated in accordance with oil and gas industry standards for these alloys. Generally, GTAW and GTAW/SMAW processes have been employed. Typical procedure details and joint properties for various thicknesses of joint in D/SDSS are shown in Figures 7 to 10. The properties identified meet common fabrication specification requirements when good practice is employed. Key points of consideration when developing welding procedure specifications are discussed elsewhere (6, 7, 8). One point to note is that for thick walled fabrications, hardness of weld metal and HAZ may exceed NACE requirements. This feature is common to conventional manifold manufacture also Baxter et al (9) has shown this phenomenon to be due to residual stresses in welding causing working, and thereby hardening of the root region.

SOME LIMITATIONS OF THE HIP METHOD OF MANUFACTURE

Physical limits of HIP products are defined by the size of the autoclave. Generally HIP manifold manufacture is not possible if the manifold diameter and branch height added together exceeds 1.1m. The overall length of individual manifold sections which can be produced by HIP'ing is 3.1m. The overall weight limit is approximately 10 tonnes. HIP routes are commercially more attractive at larger diameters and in thick wall sections. Commercial "breaks" are difficult to establish, but it would appear that HIP production is best suited to manifolds 6" NB and above and with wall thicknesses of 20mm or higher.

Important areas of HIP manifold manufacture are the canister build and design. Firstly, it is essential that the hollow section can be fabricated from sheet metal. Also design must be based upon achieving minimum required dimensions following linear and volume shrinkages experienced during HIP'ing. In view of this manufacturers consider canister design as proprietary information and pre-estimates of can dimensions, for the purposes of quality control at the canning stage, are generally not available, thus final dimensions remains a question of quality of workmanship measurable only on completion of the HIP section. Estimation of dimensional changes is not precise even though some manufacturers use FEA to establish canister dimensions. However, errors in estimates of dimensional changes during HIP'ing seldom result in rejected HIP sections. This is because a near net shape philosophy is utilised which provides sufficient material to machine bores of branches to the tight tolerances required in manifold manufacture without causing minimum wall thickness limits to be lost. Figure 11 shows two HIP manifolds bolted together for pressure test purposes and demonstrates the attainment of good tolerances on branch centres. This approach reduces the impact of these alloys in providing a weight saving facility. However, this is not a significant disadvantage.

Can design must also take account of distortion during HIP'ing and final heat treatment. Heavy branch sections may sag during both processes. Whilst this can be rectified by calibration, it is better to reduce the weight of branches by introducing hollow section and or provide adequate support during thermal treatment.

Whilst powder densification processes are accompanied by volume reduction, due to removal of spaces between powder particles, the volume of the actual mild steel canister cannot change because its already 100% dense. Hence during HIP'ing volume reduction of powder is accompanied by wrinkling of the canister. This wrinkling effect due to net compaction is actually reproduced as a mirror image in the as HIP'ed surface of the component part. This feature is not particularly troublesome in practice but it is different from the smoother machined, ground or as-extruded surfaces of conventional products. In its worst case the phenomenon is manifest as a depression on the surface of the component.

It is also the case that all weldments made in construction of the canister are reproduced as a mirror image in the surface of the HIP product. Mostly these features appear as shallow impressions of no technical consequence. More significant impressions or impressions in critical areas (ie., weld preparation areas) can be smoothly ground out readily.

It is important that canisters are visually inspected prior to filling with powder. This inspection should focus on canister weld quality particularly on the inside of the can. This is because any features which exist on the inside of the canister surface will be readily reproduced in the surface of the final HIP product. For examples, WML have experienced circumstances where burn through of the GTAW weld during fabrication of the canister left 15-20mm of welding consumable fused through the welded joint and left protruding into the inside of the canister in such a position that it was obscured from view. Thus when this can was filled with powder, and HIP'ed an impression of the protruding welding wire was reproduced in the component. This feature was only observed following pickling of the product, and took the form of a 2-3mm diameter hole penetrating into the wall of the manifold. Having had this experience WML now advocate detail inspection of canister internals prior to filling with powder as part of the product inspection and test plan.

Finally, canisters must be leak proof, when filled with powder and seal welded. If this is not the case then the resultant is failure of the part to densify. This is manifest as gross porosity in the part and limited shrinkage on HIP'ing.

COMPARISON OF HIP MANIFOLD MANUFACTURE WITH CONVENTIONAL METHODS OF MANUFACTURE

Pipe and Butt Weld Outlet

This method of manufacture involves fillet welding of butt-weld outlets into pipes machined to accept the branch, butt welding of pup pieces to give the required ANSI stand up height and butt welding the flange or hub connectors on branch ends. The throat of the fillet weld in this case is specifically arranged so as to provide pressure containment and also compensate for the hole in the pipe run. Hence it is essential that the weld preparation is filled. Failure to fill the preparation will result in increased stress concentration factor (SCF) for the joint which can reduce fatigue resistance. Completely filled preparations can result in high residual stresses which give rise to distortion and sinking of the branch into the pipe run, which is not desirable.

Also, the detail of the section of the joint between the outlet and the pipe run is a continuously changing thickness and presents a sharp corner to the direction of flow of fluid. Hence, ultrasonic examination of the joint is not appropriate to check either the integrity of the joint or monitor erosion resistance through life of this critical section.

Extruded Branches (including non standard tees)

Mother pipe required for manufacture of either extruded headers (4) or non standard tees with forged branches (10) needs to be approximately 25% thicker than the minimum wall thickness required to contain the design temperature and pressure. This is because during forming of the branch section local thinning of the pipe occurs. This feature reduces the overall weight saving capability of D/SDSS alloys for process manifold applications.

Forming of extruded branches can also require interstage solution heat treatments (10) which necessitate extra man hours, furnace times and hence costs. For high pressure manifolds where thick walled components are required, it becomes impossible to extrude the full stand up height of the branch as required by ANSI design codes

(10). This necessitates butt welding of pup pieces onto the branch along with further fabrication of the flange or hub connector on branch ends.

Whilst it is possible to extrude several branches into a single section of pipe, manufacture of manifolds from non standard tees required a butt weld to be completed in between each branch of the manifold as illustrated in Fig 12. For thick, high pressure manifolds completion of such joints can be highly labour intensive and each can impart residual stresses sufficiently high to impart lateral distortion down the length of the manifold. Moreover, conventional extrusions, forgings and castings in these alloys can have grains sizes that significantly attenuate ultrasonic beams, and make this form of NDE for welded joints inapplicable. This is especially true for thick section joints. Also in thick joints there is a tendency to utilise narrow gap weld preparations to minimise the volume of deposited weld metal and reduce fabrication time. However, narrow gap joints can be prone to lack of side wall fusion defects which together with questionable NDE methods provides an unattractive combination of features for design engineers and metallurgists. Moreover, completion of thick joints leads production engineers to utilise high deposition rate welding process which require careful attention to detail in procedure qualification if required properties are to be consistently met.

Swept Outlet Manifolds

In order to overcome the difficulty of inspection associated with butt weld outlets, pipes can be prepared to accept swept-outlets. However, this involves edge preparation of the mother pipe and swept-outlet saddle to allow ease of fabrication. In D/SDSS edge preparation in welded connections is important since this primarily governs degree of dilution in the root of the joint. This factor is critical in the performance of the joint in so far as achieving adequate phase balance and corrosion resistance is concerned. Since pipe preparations to accept saddles are manually prepared for thick high pressure manifolds this can be a time consuming and troublesome exercise. Also such joints are not immune from distortion effects associated with the high volume of deposited weld metal.

HIP Manifolds

HIP manifolds do not require the availability of billet or plate of a set size or thickness to form the mother pipe run. For HIP products the metal powder provides a dimensionless feedstock which can be used to produce any size of manifold within the confines of the autoclave. This can provide a significant delivery advantage over conventional methods of manufacture.

HIP manifolds do not require the pipe run to be thicker than necessary as no thinning of the branch crotch is encountered. Moreover, reinforcement and compensation can be localised at the branch as shown in Fig 1 and not distributed along the whole of the pipe run which increases costs.

HIP manufacture removes all requirements for welding in critical branch areas. This eliminates butt weld outlet fillets, pup piece extension welds and butt welds joining hubs or flanges to the branches. In comparison with non standard tees, HIP routes also eliminates the need for thick butt weld connections between each branch. This can be a highly significant factor in favour of HIP routes when multiple branches can be built into the 3.1mm length of manifold section.

Minimisation of fabrication associated with HIP methods reduces requirements for weld procedure qualification, minimises effects of distortion and allows discerning ultrasonic inspection techniques to be employed without the degree of difficulty of interpretation encountered with conventional manufacturing routes. Ultrasonic examination of the HIP D/SDSS parts in thicknesses in excess of 100mm has been successfully employed. Also, for a recent North Sea project fabricated to BS4515, the number of weld procedures requiring qualification was reduced from 14 to 4 by selecting HIP methods of manufacture. Table 3 details the commercial impact of these factors for D/SDSS manifolds designed in accordance with ANSI B31.3.

Method	Lead Time	Relative Value	
		UNS S31803	UNS S32760
HIP	20 wks	1.01	1.00
O'LETS	28 wks	1.16	1.21
FAB.TEES	36 wks	1.80	1.90

Table 3 - Cost Comparison of 14" NB Manifold with 6" and 10" branches.

For both alloys HIP routes provides a shorter delivery and a lower cost. Also by correctly utilising the design strength of the super duplex stainless steel alloy then the manufacture of lighter, less expensive manifolds in higher grade alloys becomes a reality.

Manufacture of HIP manifolds in D/SDSS requires expertise in areas of mechanical design, HIP technology, metallurgy and welding and fabrication. As these products are critical components in offshore platforms and subsea developments continuity and integrity of quality systems throughout all phases of manufacture is essential. As these projects are usually schedule driven, logistic and project management skills are also required. These requirements call for a multidisciplinary project management approach to be employed in manufacture of HIP manifolds.

CONCLUSIONS

HIP duplex and super duplex stainless steels exhibit mechanical properties equivalent to conventional wrought products and meet all commonly called for requirements for corrosion testing and microstructural evaluation.

HIP duplex and super duplex stainless steels are readily fabricated. Fitness for purpose evaluation has demonstrated structural integrity of HIP Zeron 100 super duplex stainless steel fabrications suitable for application at design temperatures of -40°C. Compared with conventional methods of manufacture, HIP routes significantly reduces the requirement for welding.

Manufacturing procedures and quality plans for manifolds are well established and the need for a multidisciplinary project management team is identified.

HIP manufacture of manifolds in duplex alloys gives significant technical and commercial advantages compared to conventional methods of manufacture. These advantages are optimised for large diameter ($\geq$ 6" NB) and thicker wall $\geq$ 20mm) manifolds.

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Zeron 100 is a registered trade name of Weir Materials Limited.

FIGURES

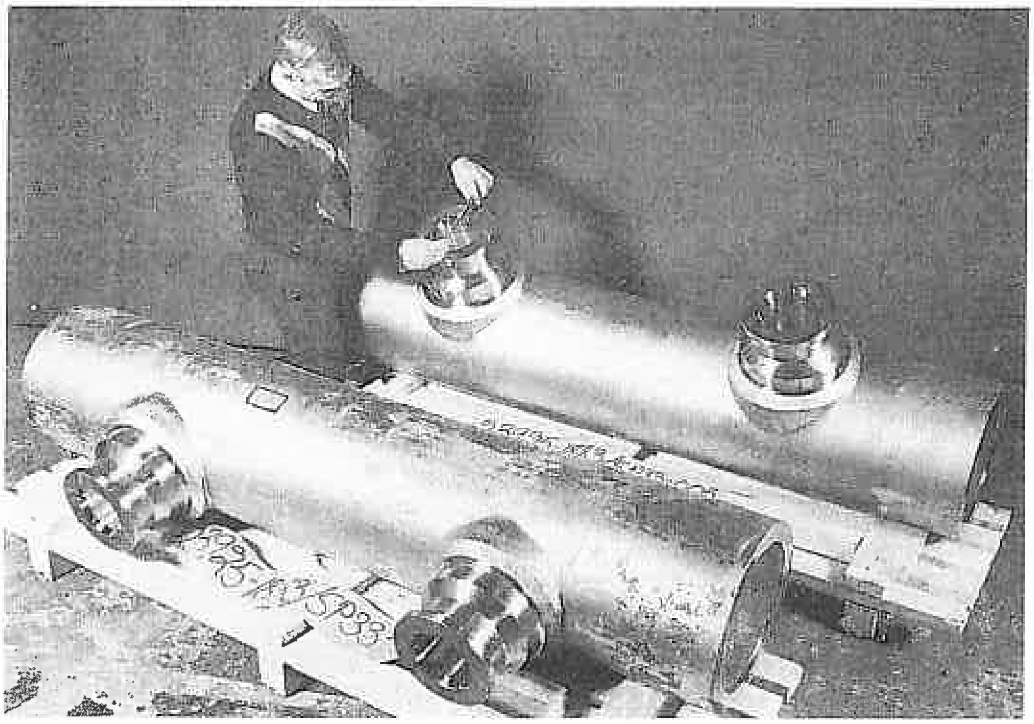


Figure 1 - 20" NB x 62mm Zeron 100 HIP Manifold Sections

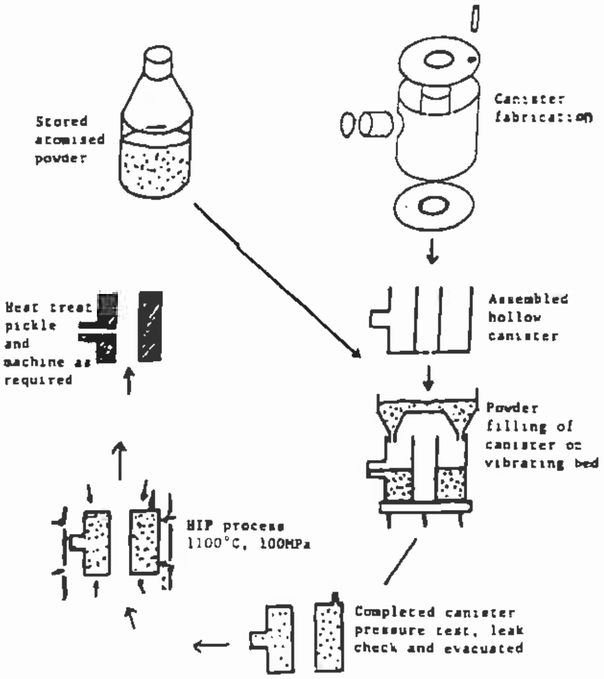


Figure 2 - Schematic Representation of HIP Manufacture

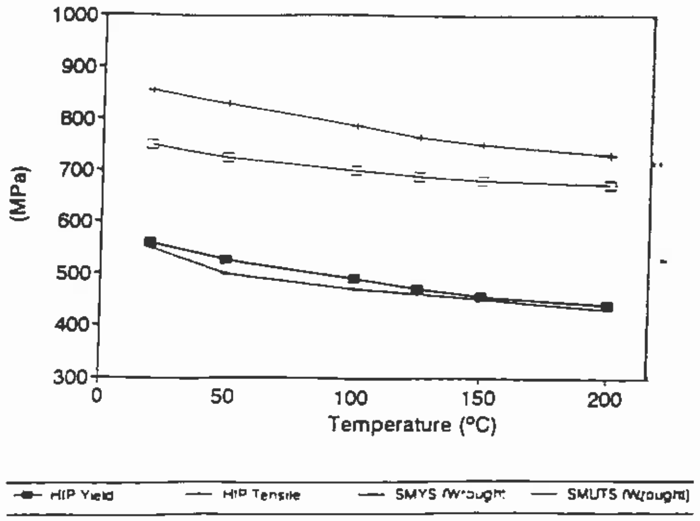
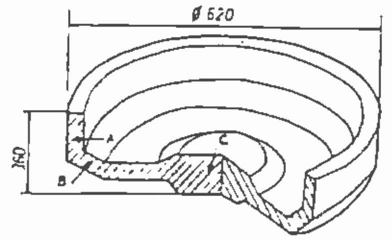


Figure 3 - Elevated Temperature Tensile Behaviour of Wrought and HIP Zeron 100



Impact Toughness KU (J) at 20°C

Location/ direction	P/M-HIP	Conventional
A/tangential	81	95
B/tangential	82	95
C/radial	81	70
C/axial	82	55

Figure 4 - Results from Testing two parts, one HIP and one conventionally forged. The HIP has isotropic properties (After Reference 1)

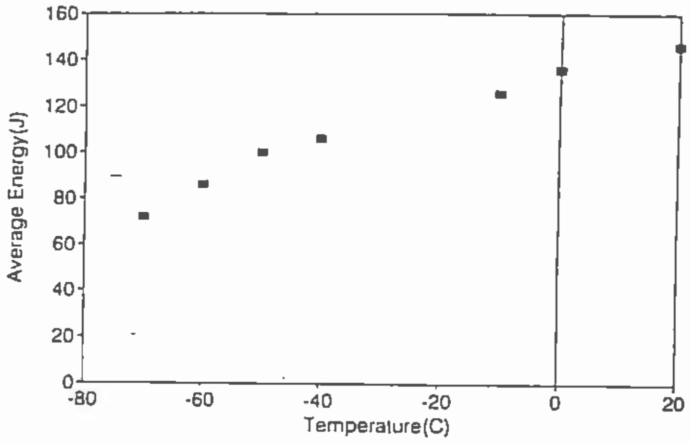


Figure 5 - Typical Charpy Impact behaviour of HIP Zeron 100 over a range of test temperatures

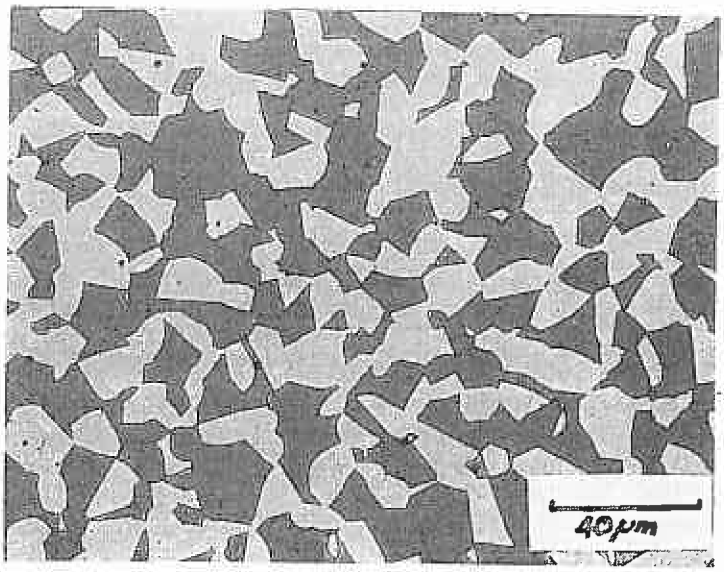
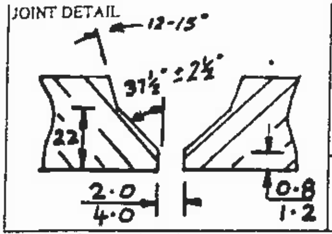


Figure 6 - Micrograph of HIP'ed Zeron 100



PROCESS: GTAW/SMAW
POSITION 1G ROTATED
FILLER Z100X 2.4mm dia/ RUN 1-2 Z100 XKS 4 0mm dia/ RUN 3-10 Z100XKS 5 0mm dia RUN 11-97
GAS SHIELD: 99.995% Ar @ 30 cuft/hr

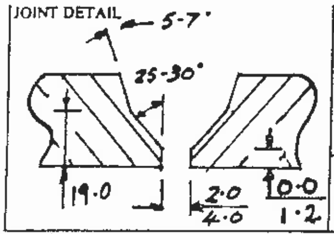
RUN No.	PROCESS	ARC CURRENT (AMPS)	ARC VOLTAGE (V)	HEAT INPUT (KJ/mm)	INTERPASS MAX
1	GTAW, DC-	125-130	12-13	1 4-1.9	20°C
2	GTAW, DC-	150-155	12-13	1.0-1.2	35°C
3-10	SMAW, DC+	130-150	24-28	0.6-2.1	95°C
11-97	SMAW, DC+	150-200	24-28	0.8-1.7	120°C

UTS: 854-898 MPa RANGE, 875 MPa AVE
BEND TESTS: ACCEPTABLE
HV10: PARENT 279-297
HAZ: 304-333
WELD: 311-342
PHASE BALANCE: 46-56% FERRITE
ASTM G48 METHOD A: 40°C: PASS

CHARPY V NOTCH@ -20°C (10 x 10mm)

WM ROOT:	38, 36, 43 J
WM CAP:	37, 37, 38 J
FUSION LINE ROOT:	60, 48, 53 J
FUSION LINE CAP:	57, 48, 55 J
FL + 2mm ROOT:	51, 45, 55 J
FL + 2mm CAP:	127, 115, 119 J

Figure 7 - Details and Properties of HIP Zeron 100 UNS S32760 Welded Joint in 12" NB x 62.0mm Thick Manifold PQR



PROCESS: GTAW
POSITION 1G
FILLER 2.4mm dia ZERON 100X
GAS SHIELD: 99.995% Ar @ 16 cuft/hr
PURGE: 99.995% Ar @ 6 cuft/hr

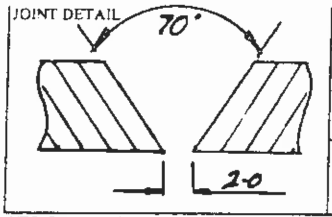
RUN No.	ARC CURRENT (AMPS DC-)	ARC VOLTAGE (V)	HEAT INPUT (KJ/mm)	INTERPASS MAX
1	107-156	12-15	1.2-1.7	57°C
2	201-215	15-18	0.9-1.2	61°C
3-37	148-295	13-19	0.8-1.8	115°C
38-46	171-222	14-19	0.9-1.4	120°C

UTS 830, 794, 798, 824 MPa
BEND TESTS. ACCEPTABLE
HV10 PARENT. 258-272
HAZ 272-319
WELD: 287-336
PHASE BALANCE 43-60% FERRITE
ASTM G48 METHOD A. 35°C. PASS

CHARPY V NOTCH@ -60°C (10 x 10mm)

WM ROOT:	143, 123, 126 J
WM CAP:	145, 147, 135 J
FUSION LINE:	96, 60, 71 J
FL + 2mm:	146, 144, 145 J

Figure 8 - Details and Properties of HIP Zeron 100 UNS S32760 Welded Joint in 8" NB x 25mm Thick Manifold PQR



PROCESS: GTAW
POSITION 1G/3G
FILLER WIRE 2.4mm dia ZERON 100X
GAS SHIELD: 99.995% Ar @ 16 cuft/hr

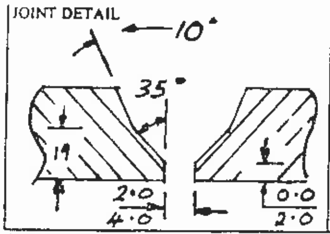
RUN No.	ARC CURRENT (AMPS DC-)	ARC VOLTAGE (V)	HEAT INPUT (KJ/mm)	INTERPASS MAX
1	130-172	13-15	1.2-1.7	104°C
2	145-168	13-15	1.1-1.2	144°C
3-6	180-195	11	0.6-0.9	130°C
7-9	180-190	11	0.6-0.7	112°C

UTS 789, 791 MPa
BEND TESTS ACCEPTABLE
HV10 PARENT 249-269
HAZ: 256-299
WELD 273-311
PHASE BALANCE 48-63% FERRITE
ASTM G48 METHOD A: 25°C PASS

CHARPY V NOTCH@ -50°C (10 x 7.5mm)

WM	95, 116, 137 J
FUSION LINE	66, 65, 75 J
FL + 2mm	103, 90, 88 J

Figure 9 - Details and Properties of HIP UNS S31803 Welded Joint in 6" NB x 9mm Thick Manifold PQR



PROCESS: GTAW/SMAW
POSITION 1G
FILLER Z100X 2 4mm dia/ RUN 1-2 / 2205 XKS 3.2, 4 0mm dia/ RUN 3-5 RUN 6-45 / Z100XKS 4 0mm dia RUN 46-50
GAS SHIELD: 99 995% Ar @ 16 cuft/hr

RUN No.	PROCESS	ARC CURRENT (AMPS)	ARC VOLTAGE (V)	HEAT INPUT (KJ/mm)	INTERPASS MAX
1	GTAW, DC-	122-134	11-13	1 0-1.3	32°C
2	GTAW, DC-	140-160	11-13	0 7-0 8	45°C
3-5	SMAW, DC+	93-108	23-25	0 6-1 1	68°C
6-50	SMAW, DC +	137-147	23-26	0 7-1 3	128°C

UTS 785, 792 MPa
BEND TESTS: ACCEPTABLE
HV10 PARENT 249-274
HAZ: 266-306
WELD. 274-317
PHASE BALANCE 46-56% FERRITE
ASTM G48 METHOD A: 25°C. PASS

CHARPY V NOTCH@ -50°C (10 x 10mm)

WM ROOT:	42, 39, 45 J
WM CAP:	45, 41, 43 J
FUSION LINE:	54, 59, 43 J
FL + 2mm:	145, 146, 145 J

Figure 10- Details and Properties of HIP UNS S31803 Welded Joint in 6" NB x 40.15mm Thick Manifold PQR

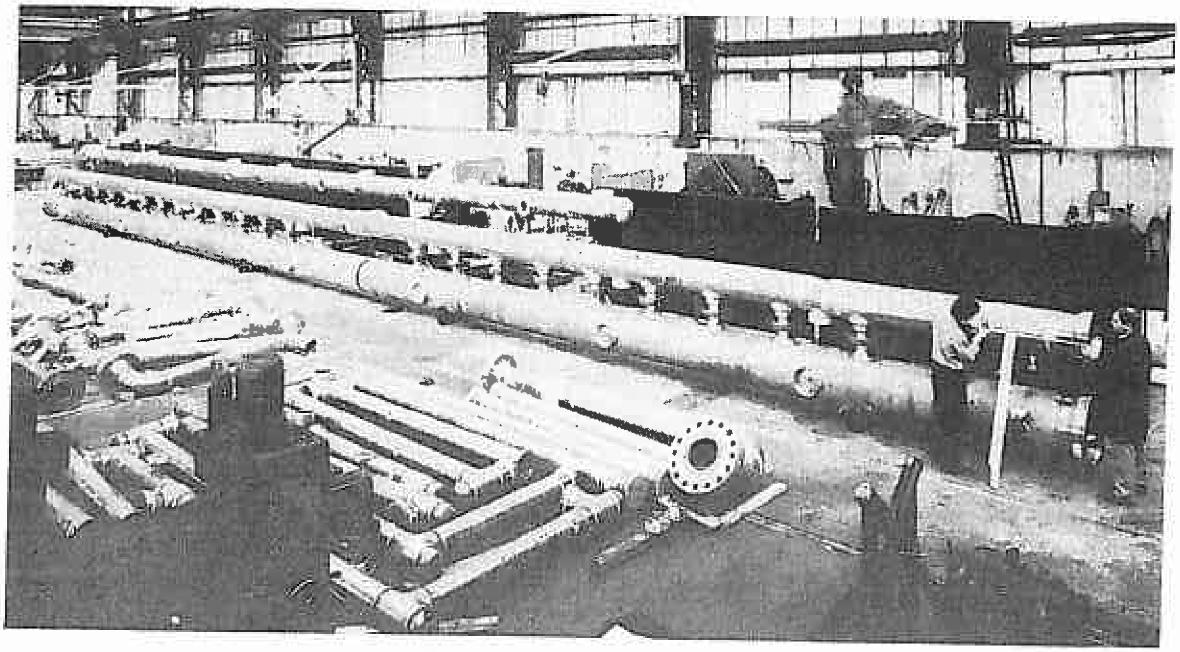


Figure 11 - HIP Zeron 100 Manifolds on Pressure Test

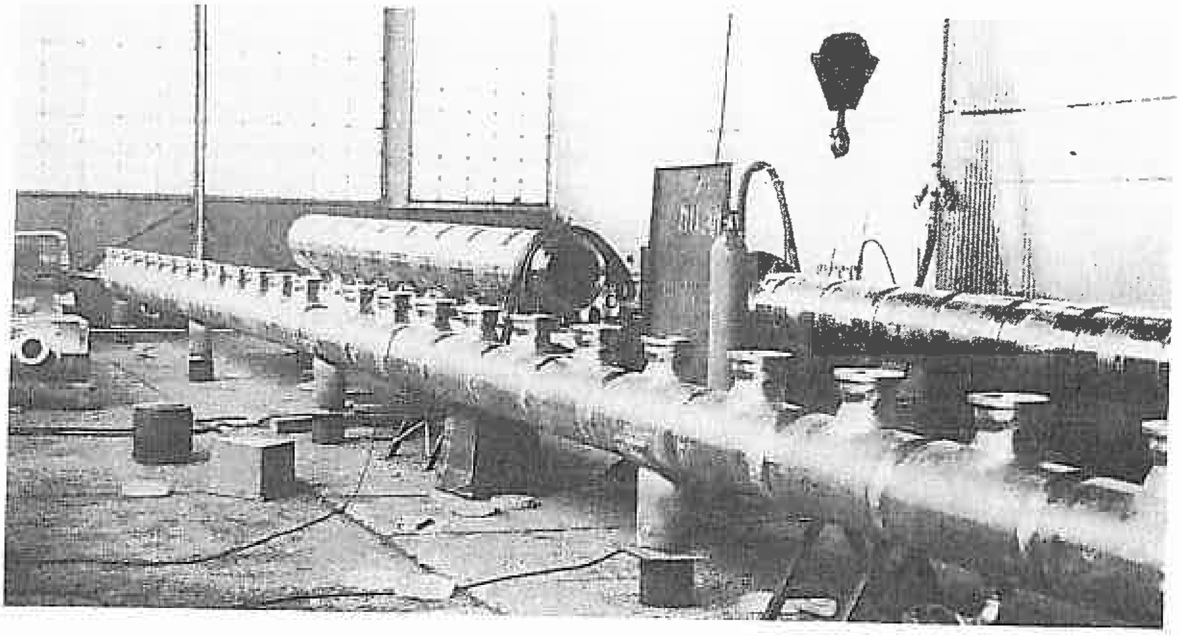


Figure 12 - Zeron 100 Manifold constructed from non standard Tee