FR 8101095 FRAMATOME-CONF-- 13

SOLIDIFICATION TECHNOLOGY IN THE FOUNDRY
AND CASTHOUSE

WARWICK - GB

DU 15 AU 17 SEPTEMBRE 1980

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SYNOPSIS

To introduce a large casting in a PWR nuclear plant migh appear detrimental to its safety when comparing with forgings or rollings. In this paper we would like to show the constant efforts of the founder in providing a product with reproducible and high quality. Furthermore a program test covering a complete investigation of a real channel head is presented ; the three following aspectshave been studied : characterisation of cast flaws by non destructive and destructive examination, homogeneity of casting and fatigue and use properties.

INTRODUCTION

The channel head of 900 MW PWR steam generators is a carbon manganese low alloy steel casting (SA 216 WCC); it is located at the bottom of the steam generator and provides three main functions :

- A containing function since it constitutes the heat exchanger of the primary coolant system
- A distribution function with regard to the reactor coolant fluid in the tubes
- A supporting function by means of four support lugs.

It weights 30 metric tonnes ; It comprises an hemispherical section (200 mm thick) with two nozzles, two manholes and four support lugs (320-450 mm thick) which are cast in one part.

The quality of such a heavy section casting is appreciated by mechanical tests, chemical analysis tests and non destructive examination. The details of these tests (method and acceptance standards) which are listed on the procurement specification in accordance with " CPFC " (Customer requirements)and French regulations, will be described when dealing with the foundry shop manufacturing process.
Furthermore FRAMATOME (the manufacturer) and EDF (the user) have decided to investigate completely a real channel head as supplied by the foundry shop here CREUSOT-LOIRE, called " Experimental Channel Head ".
The three specific tasks of the project are the following :

- Characterization of cast flaws by non destructive and destructive examinations
- Homogeneity of the casting
- Fatigue and use properties

In this report we would like to present the results available at the moment and draw the first conclusions. This program was announced in the paper presented in PARIS at the 2nd Conference about " Special steels and nuclear energy " [8]

1. MANUFACTURE OF CHANNEL HEADS IN THE FOUNDRY-SHOP

1.1. Problems inherent in large castings

It should be appreciated that all large castings contain defects. It will be shown below that all necessary precautions are taken during manufacture to minimize, detect and repair defects properly and effectively so as to leave only surface defects, hence those presenting the greatest dangers in terms of safety, smaller than 5 mm in the case of round indications and smaller than 2 mm in the case of linear indications.
By applying severity level 1 of the ASTM Reference Radiographs for areas subject to the greatest stresses (connecting lip, nozzle ends) and severity level 2 of the ASTM Reference Radiographs for other areas of the C.H.C. it is possible to limit the size of internal defects detected through radiographic examination.
Types of defects encountered are :

Internal defects : .shrinkage cavities, micro-shrinkages
.blowholes, gas porosity
.hot cracks
.sand and slag inclusions (parent metal, weld metal)

Surface defects : .cracks and microcracks
.gas prosity
.inclusions
.mal practice defects, (Burin strike, are strike, electrode tears).

The above mentioned defects are primarily associated with :

- the steel making and casting processes (exogenous inclusions)
- the solidification process
- the presence of gas
- repairs

Surface cracks that have been observed on the outside surface of all first steam generator C.H.C., irrespective of their manufacturing process are characterized by a series of highly oxidized small cracks. Surface decarbonization with thermal attack of the grain boundary caused by the oxidizing atmosphere takes place.
The carbon % has been determined as a function of the distance to the casting surface. Confirmation that surface decarbonization actually takes place has also been obtained by taking hardness measurements.
To determine the degree of decarbonization at a given point on the casting a carbon content equal to 90% of the nominal content has been fixed as the upper value of the decarbonized area.

The compositions of the facing sands and ZrO_2 coating are particularly significant. It has been possible, for instance, to reduce the decarbonization from 15 mm to 3 mm by mixing a percentage of recarbonizer (made by CREUSOT-LOIRE) to the sand and ZrO_2 coating.

1.2. Chemical composition control of the steel.

The composition of the SA 216 WCC steel is specified in Section II of the ASME Code. Nevertheless, restriction have been made to the limits of composition authorized by ASME according to customer requirements (EDF-CPFC*) and with a view to optimizing :

- weldability : C, S
- toughness : C, P, S

Element	C	Mn	Ni	Si	Cu	Cr	P	S	V	Mo
Max. %	0.25	1.20	0.50	0.55	0.25	0.30	0.020	0.020	0.020	0.25

with Cu + Ni + Cr + Mo + V $\leqslant$ 1%

The following points should be noted :

. limitation on recommended carbon content to 0.24 % max. (for 0.25% tolerated by the ASME).
. attempt to obtain lowest possible S and P contents
  S % recommended $\leqslant$ 0.010 for 0.45 in Code
  P % recommended $\leqslant$ 0.015 for 0.40 in Code
. attempt to obtain lowest possible vanadium content
. careful aluminium killing (250 ppm) to control austenitic grain size
. Cu content limitation
  0.25 % for $\leqslant$ 0.50 % tolerated in Code.

In addition, a special effort is made to maintain composition within a narrow range so as to supply products which have uniform quality. The low S and P contents recommended for these castings are obtained by using the double-slag steel-making technique. Moreover careful selection of metal strip used for the furnace runs is required.

Figure 1 which represents chemical composition histograms of 69 CREUSOT-LOIRE Channel Heads clearly illustrate the points made above .

1.3. Moulding and casting technique

Given the general shapes of the part which is represented in figure 3, voluminal masses of the support lugs, nozzles and manholes and acceptance standards of the radiographic examination (Severity level 2 of the ASTM Reference Radiographs), the feeding system to be provided for the part requires a highly complex riser system. It consists of :

- risers
- feeders-paddings
- chills intended to control solidification
- crack resistant ribs

The purpose of these artifices is to minimize defects inherent in a given steel casting such as shrinkage cavities, gas porosity and hot craks.

They are the culmination of successive improvement made to the manufacture of these castings and constitutes the know-how of the Founder.
The pattern and core boxes are made in hard wood for serial production.
Dimensional precision is checked prior to the assembly of a new part.
The contraction which occurs during solidification necessitates certain precautions for the manufacture and respective position of the mould and cores. The compressibility properties of sands must be very good.

* C.P.F.C. : EDF Manufacturing and Checking Requirements Manual

The mould is made of extra pure silicious facing sand and coated with a layer of graphite and zircon. These latter two elements make it possible to avoid respectively surface decarbonization and obtain a particularly smooth surface.

The cores are made in high heat resistance chromite to prevent them from being damaged as a result of long service at high temperature.

Casting, which requires 100 tonnes of liquid metal, is performed using one ladle so as to obtain a regular pouring rate.

The mould is in cup-position - lip on top side - and the bottom gates and ingates are designed and arranged to obtain a laminar flow : this makes it possible to prevent damage to the cast walls and the formation of exogenous inclusions.

1.4. Finishing operations : Heat Treatments

The cooling period in the mould is approximately ten days. At this point, the casting is shaken out of its pattern to activate cooling and minimize stresses due to contraction.

Once shaken out of its pattern, the casting is pre-heated in a heat treatment furnace at 250°C ; this heat treatment is carried out to make possible the discard of risers by a cutting torch and at a temperature greater than 150°C.

The heat treatment is very important. Its purpose is to optimize the mechanical properties of the casting.

The heat treatment consists of :
- normalization at 950°C followed by air cooling ; its purpose is to obtain initial refining of the structure
- water quenching after austenitization (870-900°C) designed to minimize grain growing. Water quenching was chosen to increase the cooling rate and obtain a refined structure.
- tempering at a temperature above 650°C in accordance with the applicable procurement specification.

To ensure reproductibility of these treatments, precautions are taken
a) during prediods in the heat treatment furnace (the temperature of castings is controlled using thermocouples) and
b) during quenching keeping time checks on all operations performed.

Test coupons which are shown in figure 3 are integral with the casting throughout the duration of heat treatments : they are detached before the start of machining.

1.5. Mechanical properties

Mechanical tests, as required by procurement specification , are performed on two coupons after post weld heat treatment :
- coupon X located on the lip (cf. figure 3)
- coupon Y located at the end of one nozzle (cf. figure 3)

The specified values are the following :

Tensile tests					Impact test KCV	
20°C				343°C	0°C	
$Re_{0.002}$(MPa)	Rm (MPa)	A% (5d) 4d	%	$Re_{0.002}$(MPa)	Min. one specimen	Average 3 specimens
≥ 276	≥ 483	≥(20) 22	≥ 35	≥ 200	≥ 5	≥ 7

The impact test requirement have been made widely above to the limits authorized by French regulation (Arrêté Nucléaire of 2.26.1974) : KCV at 0°C ≥ 5daJ/cm^2

for materials with Rm max. ≤ 600 MPa.
Figure 2 shows histograms of values obtained for tensile and impact tests on both coupons from 69 channel heads.
These values are always above the specified values, most of them with an appreciable safety margin.

1.6. Non destructive examinations and repairs

Before examination the channel head is subject to some sizing operations :

- machining of the entire inner surface, connecting lip, nozzles and manholes.
- grinding and gouging where necessary on the outer surface

These operations remove all defects located on the surface of the part, particularly defects usually associated with surface decarbonization.

1.6.1. *Internal soundness examination*

The part undergoes radiographic examination using linear accelerator.
Acceptance standards for areas subject to the greatest stresses, the connecting lip and nozzle ends, are more stringent than for the rest of the casting (severity level 2 of the ASTM E-280 Reference Radiographs).
Severity level 1 of the ASTM E-71 or 446 Reference Radiographs must be observed for these areas. In all the cases category D, E, F and G defects are not acceptable.
All unacceptable indications are removed or reduced to an acceptable size.
These operations may be performed in several periods.
After each period, a stress relief treatment is performed. The duration of such treatment varies according to the thickness of the repair necessary.
Examination and repair operations are carried out successively so long as unacceptable defects persist. There are generally two to three sequences.
Excavations carried out subsequent to radiographic examinations are systematically noted.

1.6.2. *Surface defects examination*

Surface defects are detected by magnetic particle examination, which involves passing a current through the product (Prod Technique).

Defects are removed by gouging. Magnetic particle examination is again performed on surface excavations resulting from defect removal. Readings are taken, after which the excavations are filled by welding.

By carrying out a succession of operating sequences (magnetic particle examinations, excavating, repairs, stress relief treatment), surface indications on the channel head are reduced as followed :

. linear indication ≤ 2 mm
. round indication ≤ 5 mm

1.6.3. *Repairs*

After defect removal (surface and internal defects) surface excavations are examined by magnetic particle examination.
Filling by welding is then performed using the manual and semi-automatic processes:

manual process : Shielded Metal arc Welding
semi-automatic process : Gas Metal arc Welding

This operation, carried out in accordance with the applicable welding repair specifications, requires compliance with pre-heating and stress relief requirements and welding and welder approval requirements.

1.7. Conclusion

All the operations described above provide the SA 216 WCC grade steam generator channel head with a high quality. The main parameters have been determined and are verified constantly so as to provide a product of reproducible quality and high reliability and safety.

Nevertheless, if such precautions are sufficient for conventional structure it is not the case for nuclear components ; Particularly the introduction of a large casting in the primary section of a PWR might appear detrimental to its safety, when comparing with forging or rolling products.
Consequently, EDF (the user) and FRAMATOME (the manufacturer) have decided to carry out a complete investigation of a real channel head as supplied by the foundry-shop by testing not only procurement coupons but also samples taken out of singular zones (under risers paddings, chills, ..).
The three specific tasks of the project called " Experimental Channel Head (ECH) program " are as follows :

- Significance of non destructive examinations and characterization of cast flaws.
- Homogeneity of the casting
- Fatigue and use properties

2. SIGNIFICANCE OF NON DESTRUCTIVE EXAMINATION AND CHARACTERIZATION OF CAST FLAWS

The validity of the analysis, concerning fast fracture resistance of such a casting depends on the morphology and dimensions of the defects likely to remain after examination and repair. Thus, the investigation is aimed at a closer assessment of all the types of defects likely to show up as indications. At the same time, we shall try to appreciate the ability of the non destructive examination methods to see these defects.
Non destructive examinations have been performed on the E.C.H. after quality heat treatment as required by the procurement specifications.

2.1. Magnetic Particle examination

All the unacceptable indications having appeared during magnetic particle examination have been listed according to their nature (metallurgical or mal practice) and their location (under riser, padding, chill ...).
The flaws corresponding to metallurgical indications were identified by visual or destructive examination as sand and slag inclusions, surface cracks and microshrinkages.
Concerning mal practice indications their origin was settled to be in relation with manufacturing operating as manipulation, grinding, gouging and weld repair : Burin strike, arc strike, electrode tears.
The general conclusions resulting from this examination are the following :

- great proportion of mal-practice defects
- the microshrinkages are mainly located on the inner surface section of the channel head corresponding to the paddings center line ; these flaws look similar to those observed in the axial V segregation zone of large ingots [1] : their presence is consequently in relation with the mould pattern design.
- Concerning the other metallurgical indications a few of them ,sand inclusions,were detected under risers.
- No indication was noted on the part surface in contact with chills.

All these flaws could be easily removed by grinding.
Furthermore, magnetic particle examination was performed, after weld repair in and around the repaired areas : these examinations did not yield any relevant indications.
As soon as these conclusions were known some actions were taken in the foundry shop to decrease the proportion of mal-practice defects. The expected improvment were achieved :

- reduction of examination time
- reduction of repair time
- reduction of time of stress relief heat treatment and of course reduction of procurement time without any change in quality level.

2.2. Internal soundness examination

2.2.1. *Radiographic examination*

According to the procurement specification radiographic examination, 100% in volume, was carried out on the E.C.H.. Similar to the procedure followed for surface examination, the internal defects, whenever acceptable or unacceptable with respect to the requirement specification, would be subject to complete identification. This identification is now being done but not yet finished although the results of radiographic examination are available. Most of indications revealed on radiographic films were identified as category C (shrinkage) indications with the maximum severity level of three according to the ASTM Classification; the few others are indications of Category A (porosity) and Category B (Sand and slag inclusions) according to the same classification.

Some of this first type of indications, category C, that are the most important in size, present channel type morphology and are mainly located in the section of channel head under all the paddings except one;the base of this last one was fitted with two thick direct chills.
Macrographic observations (*Sulfur prints*) confirmed this influence of direct chills [2] on the casting internal soundness as can be seen on figure 4 ;in this last case the ghost-lines are rejected out of the part. The mechanism of formation of these ghost-lines (or inverted V segregation) was treated by FLEMINGS [3] when speaking about soundness of large ingots ; Regarding the mass of the paddings it is not surprising for similar singularities to show up.
These results seem to indicate that some relationship exist between the presence of ghost-lines and channel type morphology defects revealed by radiographic examination ; nevertheless for confirming this conclusion one will have to wait till the defects are observed by destructive examination.

For such a purpose it was found that stereoradiography could be successfully used to isolate, in the part thickness, small plates of casting which contains the defects. Subsequently, this method was introduced in the manufacturing operations of channel head for locating in thickness the unacceptable defects before repairs.
Following this analysis ,actions were taken in the foundry shop to change progressively the mould pattern design :

- reduction of important mass as paddings
- more judicious location of chills

The expected improvment was acheived : important decrease of the number of channel type morphology defects found when carrying out the radiographic examination.

2.2.2. *Ultrasonic examination*

As required by the procurement specification ultrasonic examination (transverse and longitudinal waves), was performed on E.C.H.. This examination did not reveal any important indications and it was not possible to connect them with radiographic indications. These indications were spot indications their amplitude never exceeded the reference level. Referring to these results and those of manufacturing operations, generally speaking (no unacceptable indication to remove after this examination) it was decided to cancel ultrasonic examination on channel heads ; Nevertheless the repaired areasare always subject to ultrasonic examination.

3. HOMOGENEITY OF CASTING

Considering the large quantity of steel necessary for manufacturing such a casting , test coupons may not obviously appear to be sufficiently representative of the various sections of the part.

Thus a test program aimed at showing the homogeneity of the casting was carried out after all manufacturing sequences had been perfomed.
This investigation deals with chemical composition and mechanical properties throughout the thickness.

3.1. Chemical composition

The test program includes complete chemical analysis in the following sections of the E.C.H.

- under chills
- under risers
- under paddings
- at the extremity of a padding

The results listed in the table below didn't show any significant segregation.

LOCATION		C %	S %	P %	Mn %	Cu %
under chill		0.220	0.007	0.007	1.05	0.095
under riser		0.195 0.216 0.208 0.208	0.005 0.006 0.006 0.005	0.008 0.009 0.007 0.007	1.02 1.08 1.07 1.04	0.115 0.100 0.095 0.095
under padding	extremity	0.213	0.006	0.007	1.03	0.115
	base	0.202 0.176	0.006 0.006	0.007 0.007	1.08 1.03	0.120 0.115
out of chill riser padding		0.201 0.192	0.005 0.005	0.006 0.007	1.03 1.03	0.115 0.115
Test coupons	x y	0.205 0.207	0.006 0.007	0.004 0.004	1.05 1.04	0.110 0.104

3.2. Mechanical properties

The usual mechanical tests (Tensile and Impact tests) have been performed on five sections of the E.C.H. casting. Those sections had been choosen with respect to riser system and stress repartition in service :

Section A	under chills	
Section B	under a padding	
Section D	under a riser	
Section C	on the lip	areas subject to the
Section E	on nozzle end	greatest stresses

According to the sections some of the five following thickness levels have been tested : inner surface, inner I/4 T, 1/2 T, outer 1/4 T and outer surface

Figure 5 shows the values obtained for tensile and impact tests from the different sections throughout the thickness.
The conclusions we can draw of we consider these figures are the following :

- no problem with respect to required values except perhaps for impact test in section A ; nevertheless for these last tests we can notice that the values obtained from E.C.H. test coupons are not very high when comparing with the entire population of channel heads(cf. figure 2).
- Generally speaking the result ranges and result levels are comparable with those obtained from E.C.H. test coupons.

4. FATIGUE AND USE PROPERTIES

This task involved crack growth rate low cycle fatigue and toughness tests on metal taken from E.C.H.

These tests are now being done but not yet finished. Thus it is not possible to present them.
Nevertheless, we can remind the results obtained, and already published, from tests performed on same material (remaining test coupons metal of manufacturing channel heads).

4.1. Fatigue

4.1.1. : *S – N Curves*

Fatigue tests were carried out at room temperature and at 320°C for FRAMATOME with purpose to determine S-N curve for SA 216 WCC material.
When comparing with forging (SA 508 Cl.3) or plate (SA 533 Gr.B Cl.1) materials the results obtained are sligthly inferior for higher strains and similar for intermediate and lower strains [4 - 5] .
Furthermore, these results have been located with respect to the ASME Code design curve ($Rm \leqslant 552$ MPa).
Of course the ASME Code curve is widly under the experimental values and a safety factor range between 10 and 20 is obtained when considering the cycle number.

4.1.2. *Crack growth rate*

Crack growth rate tests have been performed for FRAMATOME at room temperature and at 320°C in the ambiant air (frequency : 10 Hz and $R = K_{min.}/K_{max.} = 0.06$)

The results published by BERNARD,HOUSSIN and SLAMA [5] show that the behavior of SA 216 WCC steel is similar to that of reactor steel forgings SA 508 Cl.3.

4.2. Toughness K_{Ic}

FRAMATOME did not already conduct these tests : nevertheless the results obtained by GREENBERG and SHABBITS [6 - 7] are available on the same material. They showed particularly, basing on these results, that the critical defect size likely to produce fast fracture is greater than the channel head wall thickness : it is a case of leak before break.

5. CONCLUSION

The control in foundry shop of the main parameters, owing to provide a manufacturing product (such as a channel head) with a high and reliable quality, is a complex problem.
The founder know-how and the information resulting from various test programs and specially Experimental Channel Head test program have made it possible first to bring some improvments in the practice of non destructive examination, second to determine the nature and origin of singularities likely to show up and third, subsequently, to understand solidification problems of such a complex casting. Concerning this last observation we have shown the positive action of chills when judiciously located and in contrary the detrimental effect of important liquid metal masses such as paddings.
Furthermore, a program test attached to the casting homogeneity has been performed on E.C.H. ; the results did not reveal any significant singularity.

ACKNOWLEDGEMENTS

The writers wish to acknowledge the invaluable assitance of CREUSOT-LOIRE Laboratory and EDF local inspection in coordinating the manufacturing process operations and test program. We are indebted to CREUSOT-LOIRE Foundry-shop for having made possible to delay some manufacturing operations on E.C.H. for special investigations.
The program was sponsored by ELECTRICITE DE FRANCE and FRAMATOME Engineering in PARIS.

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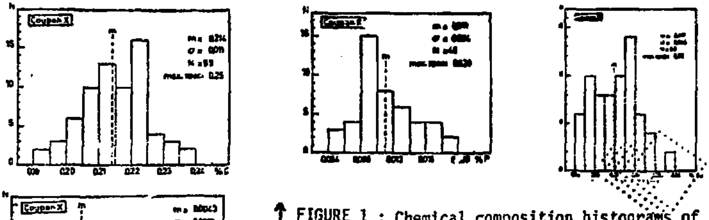
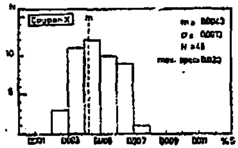
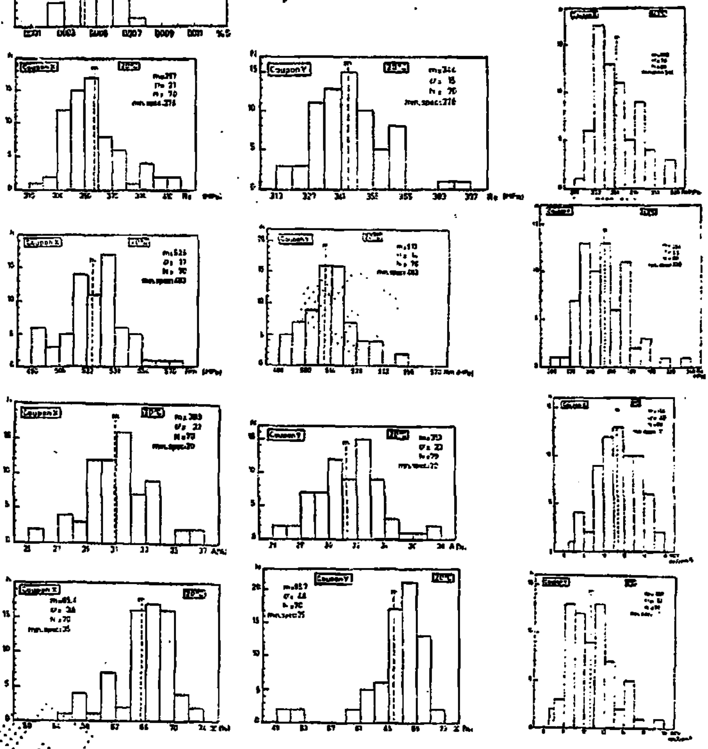




↑ FIGURE 1 : Chemical composition histograms of channel heads (product analysis)

↓ FIGURE 2 : Mechanical properties histograms



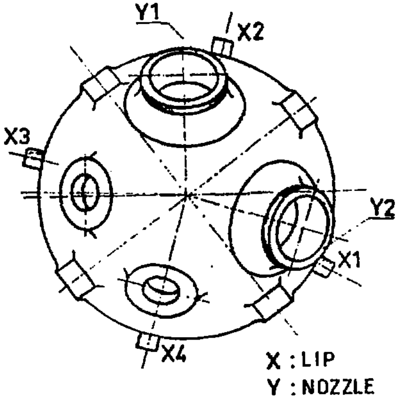
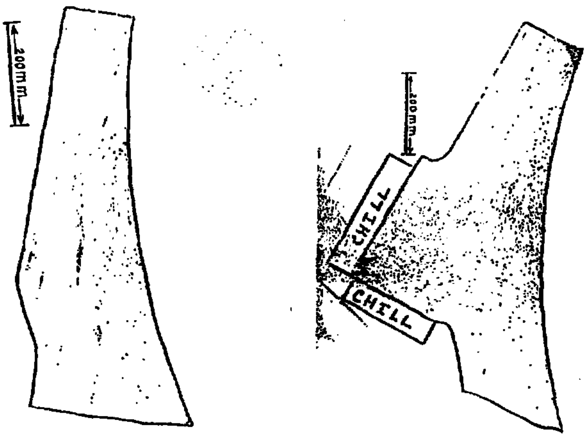


FIGURE 3 : Representation of channel head and locations of coupons X and Y



a) without chill

b) with chill

FIGURE 4 : Sulfur prints

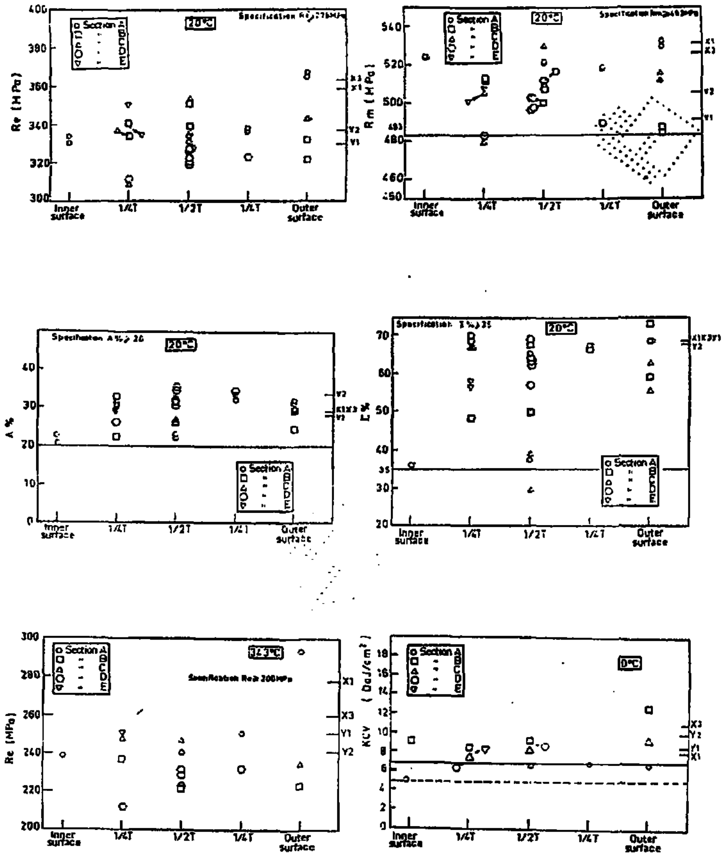


FIGURE 5 : Tensile and impact tests results on Experimental Channel Head