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WELDING AUSTENITIC STEEL CLADS FOR FAST REACTOR FUEL PINS

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1. Introduction

Austenitic steels are generally used to clad mixed oxide fuels for fast neutron reactors.

Within the scope of project SNR-300, steels WN 1.4961, WN 1.4970 or 12 R 72 HV, WN 1.4981 and WN 1.4988 (Table I) have been the subject of in-pile and out-of-pile experiments for several years. These steels are niobium, vanadium or titanium stabilized and have a completely austenitic structure, as is shown in Schaeffler's diagram (fig. 1).

The improved creep behavior of these steels and their good sodium corrosion resistance justify their use as cladding for fast reactor fuels.

As part of the Belgian program for the development of fuels for fast, sodium-cooled reactor cores, the SCK/CEN-Belgonucleaire joint plutonium group has been given the responsibility of developing welding techniques applicable to the fabrication of plutonium pins.

2. Welding fast reactor fuel clads

The TIG (Tungsten Intert Gas) process is currently used for welding plugs on fuel pin clads. In this process, an electric arc is established in an inert atmosphere between the parts to be joined together and a tungsten electrode that does not take part in the fusion.

The direct polarity arc is generally DC fed, the electrode is negative and the parts are positive. The energy dissipated in the arc melts the edge of the parts to be assembled and adhesion is effected without a filler metal. TIG welding of stabilized austenitic steel clads has revealed some crack sensitivity in the welded zone.

These steels are in fact classified by the Belgian Institute of Welding in a category of steels necessitating special precautions (1).

The Bystram zones shown on Schaeffler's diagram (fig. 1) confirm the hot cracking tendency observed when these steels are used under certain conditions. The cracks observed in these welds are inter-crystalline and often appear in the weld metal, in the bead center; they develop along the bead axis, from the surface to a certain depth in the weld metal (2).

These cracks often occur at the junction of crystallization edges of the weld metal, at the place where impurities have been jumped up by solidification. The presence of long dendrites seems to promote crack propagation at grain boundaries. Crack size and frequency increase in the arc extinction zone, commonly called the crater. Some cracks have also been observed at the root of the weld, i.e. at the junction of the weld metal, clad and plug.

By its configuration, this point constitutes a place for a crack to begin. Some cracks were also observed in the weld junction bewteen the weld metal and the base metal, but they were generally associated with large precipitates. (1).

Hot tensile tests on a Gleeble machine were carried out during simulation of a welding cycle. These tests showed that the mechanical properties revealed during cooling between 1300 and 1100°C were smaller than those noted during heating.

Metallographic examination of simulation specimens revealed grain boundary enlargment coupled with the presence of micro-cracks. According to a number of authors (3 to 9), hot cracking takes place during cooling and as a result of the segregation, at the grain boundaries, of non-metal compounds with a relatively low melting point. The role of certain elements which render welding difficult, such as sulphur, phosphorus, silicon and niobium, has been the subject of numerous studies (3, 5, 6, 7, 9).

The poor solubility of these elements in austenite explains their rejection at grain boundaries during cooling, both in the weld metal and in the heat-influenced metal. The mediocre mechanical properties of these compounds precipitated at the grain boundaries reduce the permissible stress rates. But the heterogeneous cooling resulting from the welding generates high stresses which, combined with these segregations, may generate cracks.

In even small quantities, these impurities influence the cracking (e.g. : Sr 0.01%, P 0.01%). Yet, despite recourse to costly techniques such as re-fusion under a vacuum or under electro-conductor slag, the steel industry experiences great difficulty in further reducing these impurity contents. Consequently, it devolves upon the welder to adapt his techniques so as to reduce cracking risk by a discerning choice of parameters.

3. Experimental remedies in order to reduce the hot cracking of welds

3.1. Metallurgical method of avoiding cracking

Introduction of 3 to 6% of ferrite into the metal is liable to reduce the volume of non-metallic compounds precipitated at the grain boundaries. Reduction in the cracking tendency and improvement in intergranular cohesion would be due to the fact that the impurities are more soluble in ferrite than in austenite (7).

The TIG welding of fuel pins is effected without filler metal. Ferrite can be introduced into the weld metal by choosing an austenite-ferrite steel plug, the composition of the steel being such that, allowing for dilution, the weld metal contains 3 to 4% ferrite.

This method solves the problem of cracking in the weld metal but is inoperative on cracking in the clad base metal.
This solution was envisaged but was not experimented with on a large scale as it was not compatible with the specifications imposed at the time of the tests.

3.2. Adaptation of the weld-heat operation

3.2.1. General

One cracking remedy consists of reducing the cooling speed so as to limit the severity of the shrinkage stresses. The pre-heating and post-heating generally used are difficult to carry out economically when welding fuel rods. On the other hand, increased heat input during welding makes it possible to homogeneize temperatures and slow down cooling to some extent.

3.2.2. Finding a solution to cracking in the final crater.

In TIG welding it is customary to extinguish the arc very progressively in order to efface the crater. During the first tests carried out in the laboratories of the SCK/CEN-Belgonucleaire joint plutonium group on steels WN 1.4988 and 12 R 72 HV (10), most of the welds showed large cracks in the arc extinction zone.

Systematic study of arc extinction conditions was first of all undertaken by locally melting an immobile rod by means of an arc. For an extinction rate of 10 A/ second, cracking was considerable. At 20 A/ second it was less. Finally, at 30 / A second, the melted point was crack-free.

Tests made on rotating bars confirmed these results. However, the crater size regularly increased with the extinction rate.

3.2.3. Finding a solution to cracking in the beads.

a) Finding a welding cycle.

Conventional pre-heating being impracticable, welding by several successive revolutions was experimented with in order to attain hot thermal operation.

Several welding cycles were experimented with on solid rods in order to eliminate secondary effects due to tolerance on the play between plug and clad. One pass or part-pass with reduced intensity, carried out on zones previously melted with normal intensity, caused considerable cracking; this finding excludes any possibility of post-heating by part of re-fusion of the bead.

A low intensity pass also cracked, from which it may be concluded that the welding condition has to be hot enough to avoid cracking. With sufficiently hot welding conditions, the metal cools more progressively and the shrinkage stresses have a greater possibility of taking place progressively. In addition, progressive cooling favorably influences the size and direction of the dendrites. Comparative tests carried out with the same strength but with arc voltages of 14 and 19 V resulting from the use of argon or helium as a protective gas, confirmed that conclusion.

Finally, hope of possible metal purification by successive passes proved to be misplaced.

A recent study of metal behavior during solidification (1) demonstrated that whilst the impurities are drained by the fusion front, they are nevertheless cyclically driven back behind the arc, where they constitute impurity concentration zones that are more sensitive to cracking. The cyclical aspect of this phenomenon may explain why a number of welds have cracks in the final crater : the metal in the current reducing zone is sensitive to cracking to a greater or lesser degree depending on whether the arc is extinguished before or after a flow of impurities.

Welding executed with a 10 A amperage for two revolutions, followed by fast extinction, gave the best result. Increasing the number of welding revolutions does not reduce the cracking frequency but, in the contrary, contributes to prohibitive swelling of the bead.
In addition, there is a tendency towards grain boundary swelling in the heat affected zone (HAZ). The risk of cracking in the HAZ is therefore increased.

b) Finding welding parameters.

One of the factors governing welding-heat operating conditions (10) is the heat input transferred to a given volume of metal.

The specific energy given by

$$\varphi = \eta \frac{E_I \times 60}{V_L}$$ in joules/cm of welding or in W/1cm,

is an expression of the heat input which allows easy comparison of different combinations of marameters.

η : efficiency of arc η = 80 to 85%
E : arc extinction
I : amperage
V_L : relative speed of parts and arc $V_L = V_r . \pi d.$

A priori, two combinations of parameters having the same specific energy should give the same volume of weld metal. In reality, owing to calorie diffusion by heat conductivity, for the same calorie input, the weld executed at the greater speed will be deeper and the one executed more slowly will have a bigger affected zone.

On the basis of these considerations and with a 2-revolution welding cycle, tests were made on 12 R 72 HV plugs and clads 5.24/6 in diameter.

The influence of various parameters was experimented within the following limits :

- Amperage : 6 to 20 A
- Rotation speed : 6 to 12 r.p.m., i.e. 11 to 22 cm/min.
- Position of the heat regenerators : 2 to 10 mm.

During these tests, the following observations were made :

i) The low heat inputs and close positions of the regenerators give rise to cracks. On the other hand, heat inputs that are too high cause arc undercuts and a lack of material, marked by bead concavity, most probably the result of evaporation of some alloy components.

ii) A heat input between 500 and 650 joules/cm gives rise to welds that are free from cracks and undercuts. Welds made in this parameter zone gave rise to no difficulty on the first ones with steel 12 R HV and WN 1.4988.

The same parameters applied subsequently to a batch of 12 R 72 HV steel containing 0.012% sulfur, as against 0.008% previously, did not enable the appearance of micro-cracks in the HAZ to be avoided.
However, a slight reduction in the heat input was sufficient to eliminate this difficulty. This fact illustrate the influence of slight variations in some impurity contents on the cracking sensitivity of these steels.

3.3. Drawbacks to hot welding-thermal operating conditions

Welding solid plugs under hot operating conditions and in two revolutions with fast arc extinction solves the hot cracking problem to some extent.

In addition, the rather coarse structure of the weld metal frequently comprises long dendrites, and grain boundary swelling in the HAZ is not negligible.

Bead swelling and crater size necessitate enlargement of the generally accepted diametrical tolerance on fuel rods.

These various drawbacks are at the basis of subsequent developments undertaken by the SCK/CEN-Belgonucleaire joint plutonium group.

4. Considerations on stresses appearing during welding .

4.1. General

Hot cracking is generally the result of big stresses imposed on metal which is locally weakened by the segregation of impurities rejected during cooling by the matrix in which their solubility diminishes with the temperature.

In the case of the steels used for clad fabrication, a metallurgical solution to this problem cannot be obtained at an early date. Nor does a discerning choice of welding cycle make it possible to sufficiently master solidification and shrinkage stresses, so a better design of the parts to be welded has been envisaged.

4.2. Evolution of the mechanical properties of a steel in terms of temperature .

The elastic limit R_E and Young's modulus $_E$ of a steel depend on its temperature (fig. 2 A). The maximum proportional elongation ε_E corresponding to the elastic limit decreases in terms of the temperature (fig. 2B) and is reduced to zero for the total plasticity temperature T_p situated between 800°C and 1200°C according to the type of steel.

In a first approximation, the influence of the linear expansion coefficient variations in terms of the temperature and with possible allotropic changes, can be disregarded. Admitting that simplification, the proportional heat expansion

$$\delta = \frac{\Delta}{l} = \frac{\alpha (T_1 - T_0)\, l}{l}$$

can be considered as a linear function of the temperature (fig. 2B).

The critical temperature T_c, which is around 150°C in the case of steels, corresponds to the intersection of the proportional elongations curve ε_E and the heat expansions curve δ.
Below that temperature, the heat expansions are always smaller than the permissible proportional elongations ε_E.

Consequently, a metal heated at $T < T_c$ expands elastically and reverts to its dimensions during cooling. On the other hand, heating beyond T_c is liable, under certain conditions, to cause permanent set owing to the fact that the expansions take place under elastoplastic conditions.

4.3. Conditions for the appearance of strains and stresses during the heating and cooling of a metal.

A part's residual strains or stresses may be the result of a heating-cooling cycle (12 and 13) :

1) if the part consists of an expandable material, such as metals;

2) if the heating of the part is heterogeneous;

3) if the temperature locally exceeds the critical temperature, i.e. if the material passes from the elastic state to the plastic state and vice-versa.

These three conditions are fulfilled in welding a metal when the heterogeneity and intermittence of the thermal cycle are often very high and internal clamping is difficult to avoid completely.

The following two examples illustrate the conditions for the appearance of welding strains and stresses fairly well.

First, take a rod (fig. 3 A) placed without play between two perfectly rigid, well-cooled supports. When the rod is heated, its expansion is prevented by the supports, and compression stresses appear, to compensate for the expansion by a strain of the opposite sign and of equal intensity. If the critical temperature is exceeded, plastic strains are added to the elastic ones; on cooling only the elastic strains are reversible. As shrinkage is unrestricted, there is permanent shortening $\varepsilon_{p.} l_i$ of the rod.

Then take a rod fixer rigidly to two supports (fig 3 B) and also heated at $T > T_c$. On heating, permanent elastoplastic crushing also appears. The rod thus potentially shortened will, after cooling, be subjected to tensile stresses. On the other hand, the clamp fastening will be subject to compression stresses in equilibrium with the tensile ones.

In a first approximation, the tensile stresses observed in the second case are proportional to the prevented shrinkage, i. e. finally proportional to the compression strains appearing during heating.

The elementary conclusion that follows from comparison of the last two cases is that a metal heated under the given conditions will, after cooling, be the subject of either strains or stresses, and more frequently of a combination of both.

A theoretical study (14) shows that the most dangerous tensile stresses appear in the hotest metal immediately after solidification.
Actually, the stresses appearing at high temperatures are immediately absorbed by plastic strains, since the elastic limit is small or zero.
The cracking danger lies in exhaustion of the local plastic strain capacity. This study also demonstrated that an adaptation of the welding thermal cycle modifies the distribution and extent of the strains and stresses.

One of the main conclusions to which the study led was that a reduction in the rigidity of the parts acts much more effectively on stress distribution and extent than possible changes in the thermal operating conditions do.

4.4. Evaluation of internal clamping in solid, bored plugs .

The usual solid plugs are very rigid and impose high internal shrinkage stresses on the welded metal. In order to evaluate the influence of this rigidity, a series of tests was undertaken on WN 1.4981 steel cylinders 12 mm in diameter and bored to different diameters (Table II). These cylinders were welded with the same welding current programming regulation. A slight increase in the welding current was noticed when the boring was increased. The heat flow, diminishing as the boring increased, was sufficient to change the temperature of the welding bath and influence the arc characteristics. A parallel increase in the volume of the weld metal was observed during metallographic examinations.

Specimen shortening was almost constant up to 4 mm boring (fig. 4); above that value the effect of reducing the specimen thickness on the lengthwise deformability became more and more substantial. Transversal strain measurements were effected directly for borings from 6 mm. The strain on 2 to 4 mm bored pins was evaluated during metallographic examination.

The inflexion of the curve corresponding to the 7 mm boring seemed to indicate that below that diameter a large part of the metal no longer reached a temperature sufficient to allow relaxation of the residual internal stresses.

An attempt to measure the internal stresses did not give sufficiently reliable results but it appears logical to admit that the permanent sets observed are in indication of internal stress relaxation. That relaxation takes place in the form of strain work. Under these conditions the stress level will be lower in thin specimens than in thick ones.

4.5. Conclusions

Shrinkage stresses exceeding the elastic limit may arise in the welded parts. They then bring about plastic strains in the metal which are greater than its strain capacity and which tend to cause the appearance of cracks.

Theoretical studies have demonstrated that these stresses are linked with the thermal cycle imposed on the metal and with the rigidity of the parts in the heated zones. Tests confirm that a reduction in the rigidity of the parts lowers the stress rates and may avoid exhaustion of the metal plasticity.

5. New plug design

5.1. Bored, embedded plug design

The favorable influence of a reduction in the rigidity led to the design of a bored plug in which the rigid core of the plug is eliminated by simply drilling to a depth sufficient for bead strains to be no longer prevented.

When fabricating fuel pins for an irradiation experiment in the Dounreay Fast Reactor, the welding of bored, embedded plugs on clads 5.24/6 mm in diameter in steels WN 1.4970, WN 1.4981 and WN 1.4988 was experimented with.

In order to determine their optimal dimensions, borings of 2.8 - 3.5 - 4 and 4.5 mm were made in the plugs. Solid, bored plugs were welded at amperages suited to each case, in terms of the technique developed previously (2 -revolution welding and fast arc extinction).

The solid, 2.8 mm bored plugs showed micro-cracks in the case of steel WN 1.4981. On the other hand, with the other borings, metallographic examinations did not enable cracks to be discerned.
However, under the weld, a slight deformation of the unmelted metal was visible inside the bore.

Shrinkage measurements carried out on solid plugs and 4 mm bored plugs revealed shortening of 0.00 mm and 0.07 mm respectively (15) (fig. 5A). Total shrinkage measured on the clad-plug assemblies was 0.04 mm in the case of the solid plug and 0.12 mm in the case of the 4 mm bored plug (fig. 5B). These deformations are not troublesome as regards respecting tolerances, but they show that all things being equal, the bored plug weld must be far less acted upon by internal stresses than that of the solid plug, and this is confirmed by the absence of cracks in the bored plug.

As an attempt at 1-revolution welding with relatively slow arc extinction, carried out on a 4 mm bored plug, had given an encouraging result both as regards cracks and as regards diametrical swelling, systematic tests were undertaken with this cycle.

Whereas with the solid plug and 2-revolution welding cycle the same amperage applied to the 3 grades of steel experimented with gave substantially identical penetration, it became necessary, with bored plugs welded in one revolution, to adapt the parameters to the grade of steel. In each case, this adaptation reduced the zone of influence to a minimum.

Compared with the solid plug, the bored plug necessitates a much smaller heat contribution for the fusion of the same amount of metal. For instance, to achieve a penetration of 160% of the clad thickness, a

solid plug welded in two revolutions necessitates twice a heat contribution equal to 700 joules/cm, whereas under the same conditions the 4 mm bored plug necessitates only 380 joules/cm.
This same bored plug can be welded in one revolution with only once 500 joules/cm and its diametrical swelling will then be less than half. This reduction in the heat contribution also limits the initial expansions and, consequently, the welding stresses.

Finally, the reduction in the heat contribution and modification of the heat flow bring about a favorable modification of the solidification structure and reduce the dimensions and number of the dendrites.
In addition, grain boundary swelling in the HAZ is greatly reduced. A further technological advantage of this type of plug results from increases sensitivity of the X-ray check, because of the reduction in the thickness to be traversed by the X-rays.

5.2. Design of the butt welded plug

The ideal weld is one that ensures maximum continuity between the assembled parts. Fully penetrated butt welding achieves geometrical continuity whilst presenting minimum internal rigidity owing to the fact that the boundary metal is melted over the whole of its thickness and therefore offers maximum deformability. With butt welding it is possible to achieve welds that are practically free of internal stresses.

Butt welding a plug onto a thin clad (0.38 to 0.5 mm) seems difficult, a priori, because of the correct butt-joining of the two parts. This problem was solved by giving complementary conicities to the ends of the plug and clad (fig. 6), and by equipping the welding bell with dual turning-gear which drives the two parts in synchronous rotation whilst maintaining their centering.

This technique is covered by a patent filed by SCK/CEN-Belgonucleaire Association (16).

Plugs of this type have been employed in the fabrication of fuel pins for irradiation experiments in a sodium loop in the BR 2 reactor, particularly in the case of an irradiation of mixed uranium-plutonium carbides. Welds made on this type of plug show very good geometrical continuity and very fine structure; no micro-cracks were detected during numerous metallographic examinations.

Hot and cold burst tests carried out on specimens fitted with butt welded plugs led to a slug burst along a generatrix several cm from the weld.

Tensile tests carried out on clads alone and on clads with butt welded plugs showed a reduction of less than 5% in the tensile strength resulting from the butt welding. A similar result was obtained with embedded plugs. The break took place at the junction of the weld metal and the base metal, in the HAZ. Continuity of the mechanical properties is therefore equally well achieved by this type of welding.

In conclusion, the advantages of butt welding are :

1) the geometrical continuity limits the necessary heat contribution to a minimum and thus reduces expansion and shrinkage;

2) the deformability of this type of join reduces internal stresses and the extent of the cracking problem.

6. Conclusion

When developing the TIG welding of different batches of stabilized austenitic steel of grades WN 1.4961, WN 1.4970, WN 1.4981, WN 1.4988 and 12 R 72 HV, a tendency towards hot cracking, of varying degree depending on the batch, was observed.

This is consequent upon the reduced solubility of impurities in austenite, which cause the rejection, at the grain boundaries, of compounds possessing poor mechanical properties when hot.
In particular, the role of the sulfur content seems important. Development aimed at avoiding the probability of cracking therefore necessitates adaptation of the welding method. The adoption of discerningly selected welding parameters and cycle partly solves this problem. Although the composition of these steels is favorable to be hot cracking, the latter only appears if the internal stresses reach a critical level.

Examination of stress evolution during welding led to the conclusion that reducing plug rigidity is likely to keep internal stresses to a permissible level. The idea of increasing metal deformability in the neighborhood of the weld brought up the idea of the bored plug and the butt welded plug. The butt welded plug constitutes the ideal solution to the hot cracking problem and thus achieves optimum continuity between the parts. This technique necessitates changes in existing welding bells.

The use of bored embedded plugs necessitates no change in the equipment. If a sufficiently large bore is chosen, a simple adaptation of the welding parameters enables the internal stresses to be kept to a sufficiently low level to avoid cracking.

Consequently, the replacement of solid embedded plugs by bored embedded plugs is advocated to solve the hot cracking problem observed when welding fuel pins clad with stabilized austenitic steels.

7. REFERENCES.

[1] Code de bonne pratique pour le soudage des aciers inoxydables. Institut Belge de la Soudure (1970).

[2] SNYKERS & al., Weld crack sensitivity in Nb-containing austenitic stainless steels. Topical Report BN 7006-04 (June 1970).

[3] BORLAND,J.C. & al., Some aspects of cracking in welded Cr -Ni austenitic steels, BWRA Report, British Welding Journal (Jan.1960).

[4] YOUNGER, M.A. & al., Heat affected zone cracking of two austeni - tic steels during welding, British Welding Journal (Dec. 1961).

[5] WIDGERY, D.J., Effect of sulphur and phosphorus on welds metal sophistication cracking, Metal Constr. and British Welding Journal (August 1970).

[6] POLGARY, S., Influence du silicium sur la fissuration des aciers inoxydables austénitiques soudés et particulièrement sur l'acier 18 Cr 8 Ni, Svetsaren Edition Française, 4 (1970).

[7] SADOWSKI, S., La fissuration à chaud dans les soudures austéniti-ques., Colloque Secheron (Suisse), (1969/1970).

[8] ROSENDAHL, CH., Welding of austenitic stainless steels, Svetsaren English Edition, 1 - 2 (1969).

[9] HONEYCOMBS, J. & al., Microcracking in fully austenitic stainless steel weld metal, Metal Constr. and British Welding Journal (Sept. 1970).

[10] PAPELEUX, P., SCHRIJVERS, J., LAFONTAINE, I., Soudage de l'acier au bore Sandvik 12 R 72 HV, Association SCK/CEN - BELGO-NUCLEAIRE, Rapp.Semestr.d'Avancement, Réact.Rapides, BN 7112-01 (1971).

[11] GRANJON, H., DADIAN, M., Particularités de la solidification des soudures par fusion, Soudage et Techniques Connexes, Paris, 26 5, 6 (1972).

[12] LOUIS, H., Technique de la Soudure, Institut Belge de la Soudure.

[13] GUYOT, F., Notes sur le retrait et la déformation des soudures, Institut Belge de la Soudure.

[14] PAPELEUX, P., Considérations sur les déformations et les con - traintes apparaissant en cours de soudage, Rapp. en préparation.

[15] PAPELEUX, P. et al., Développement des techniques de soudage, Association SCK/CEN-BELGONUCLEAIRE, Rapp. Semestr. d'Avan-cement, BN 7303-07 (1973).

[16] PAPELEUX, P., LAFONTAINE, I., FLIPOT, A.J., SCHRIJVERS, J. Procédé de fermeture de barreaux combustibles, Brevet Belge 781451.

[17] PAPELEUX, P., Développement des techniques de soudage, Association SCK/CEN-BELGONUCLEAIRE, Rapp.Semestr.d'Avance - ment, Réact.Rapides, BN 7210-05(1972).

TABLEAU I - COMPOSITION DES ACIERS EXPERIMENTES POUR LE GAINAGE DES BARREAUX COMBUSTIBLES DU TYPE SNR.

Nuance \ Composition %	C	Si	Mn	Cr	Ni	Mo	Ti	Nb	V	N	B	Eq. Ni	Eq. Cr
WN 1.4961	0,08	0,45	1,3	16,5	13	-	-	10 C	-	-	-	16,1	17,6
WN 1.4981	0,068	0,38	1,28	16,5	16,5	1,78	-	0,80	-	-	-	18,1	19,3
WN 1.4988	0,1	0,45	1,2	16,5	13,5	-	-	1,2	0,75	0,1	-	17,1	18,9
WN 1.4970 ou 12 R 72 HV	0,10	0,5	1,8	15	15	1,2	0,40	-	-	-	0,0165	18,9	16,9

NB : les teneurs en soufre et phosphore observées sur les lots expérimentés étaient comprises entre 0,006 et 0,012 %.

Les teneurs élevées en impuretés accroissent les difficultés de soudage.

TABLEAU II - RESULTATS D'ESSAIS DE SOUDAGE SUR DES CYLINDRES DE 12 mm DE LONG ET 12 mm DE DIAMETRE, A ALESAGES CROISSANTS.

Essais	A Alésage nominal (mm)	E Epaisseur (mm)	ΔL Raccourcissement moyen (μ)	ΔA Réduction de l'alésage (μ)	P Pénération moyenne (mm)	S (★) Section du métal fondu (mm^2)
1	0	12	13	-	0,55	0,35
2	2	5	14	(10)★	0,62	0,46
3	4	4	18	(25)★	0,74	0,77
4	6	3	34	38	0,80	0,86
5	7	2,5	52	47	0,77	0,90
6	8	2	87	109	0,85	0,98
7	9	1,5	126	205	1,23	1,52

★ non mesurable directement - évaluation effectuée lors de l'examen métallographique.

(★) mesure effectuée sur des coupes métallographiques.

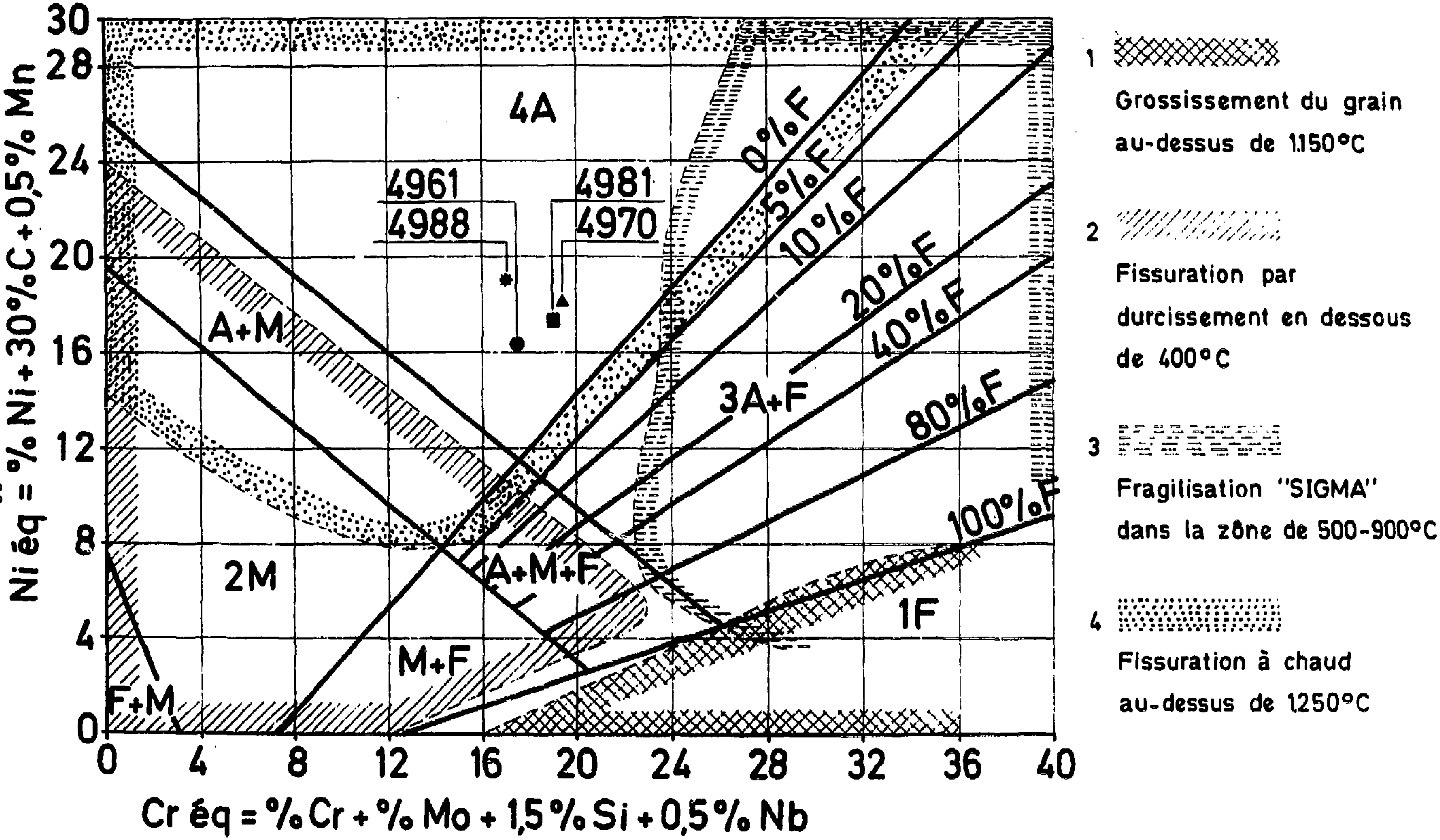

Fig 1. DIAGRAMME DE SCHAEFFLER ET ZONES DES PROPRIETES DES SOUDURES (SELON BYSTRAM) (EXTRAIT REF [1])

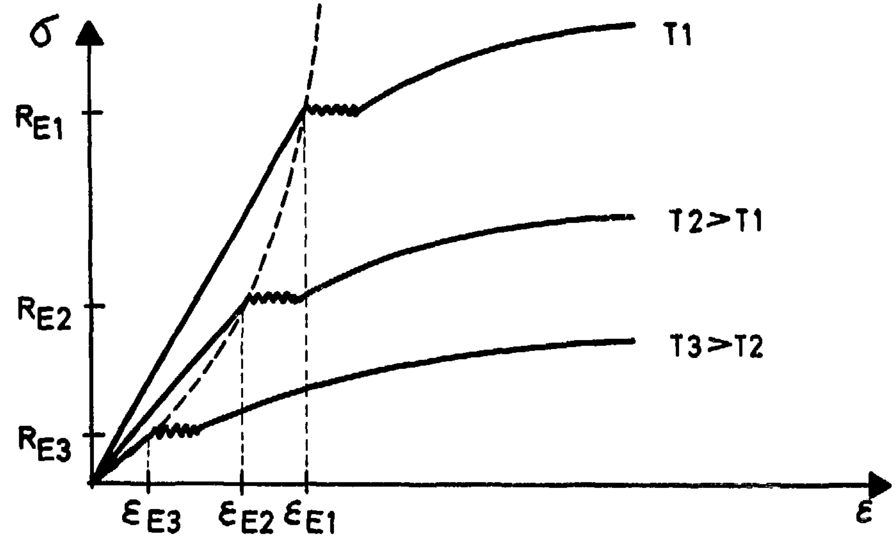

Fig 2A. LOI DE HOOKE EN FONCTION DE LA TEMPERATURE

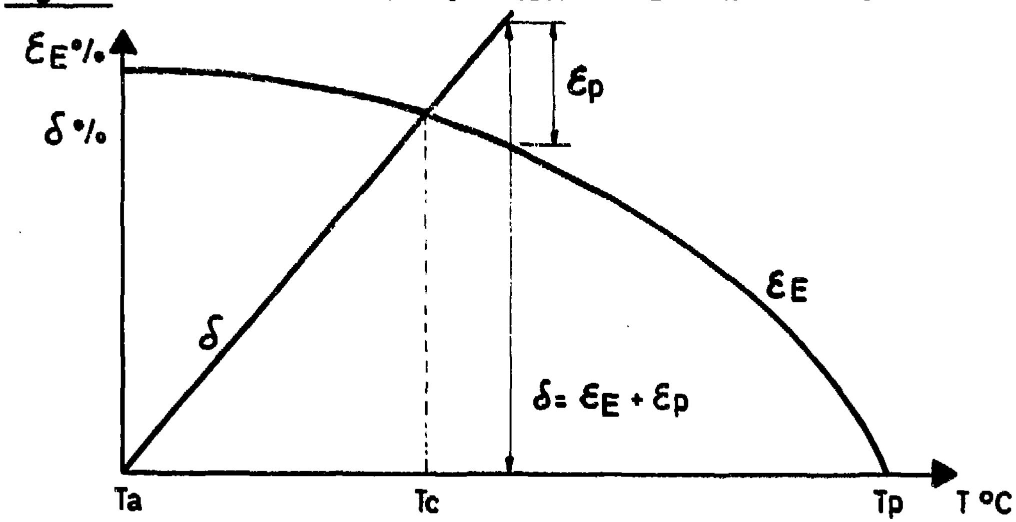

Fig 2B. ALLONGEMENT ε_E ET DILATATION THERMIQUE

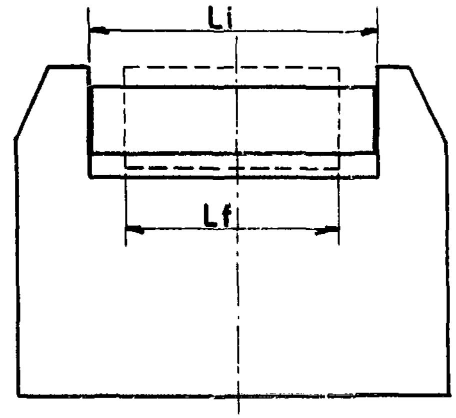

Fig 3A. DILATATION EMPECHEE ET RETRAIT LIBRE

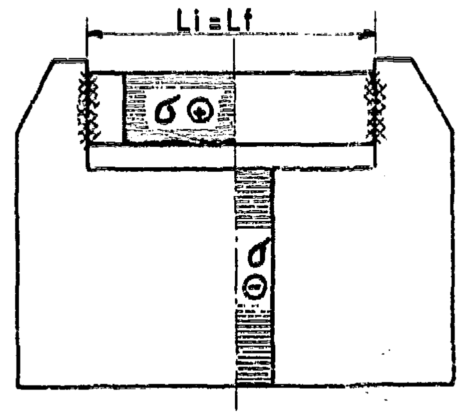

Fig 3B. DILATATION ET RETRAIT EMPECHES

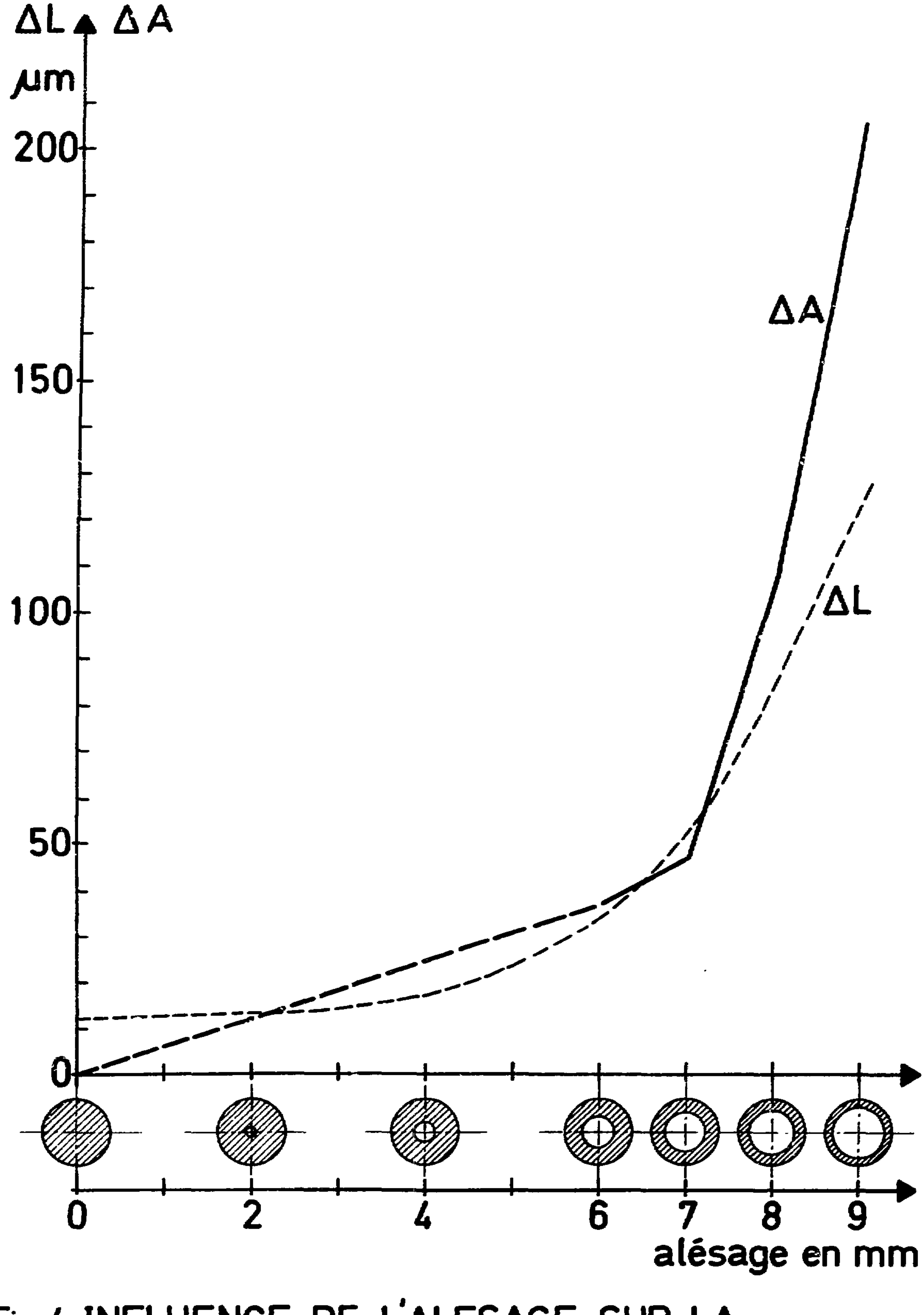

Fig 4 : INFLUENCE DE L'ALESAGE SUR LA DEFORMABILITE

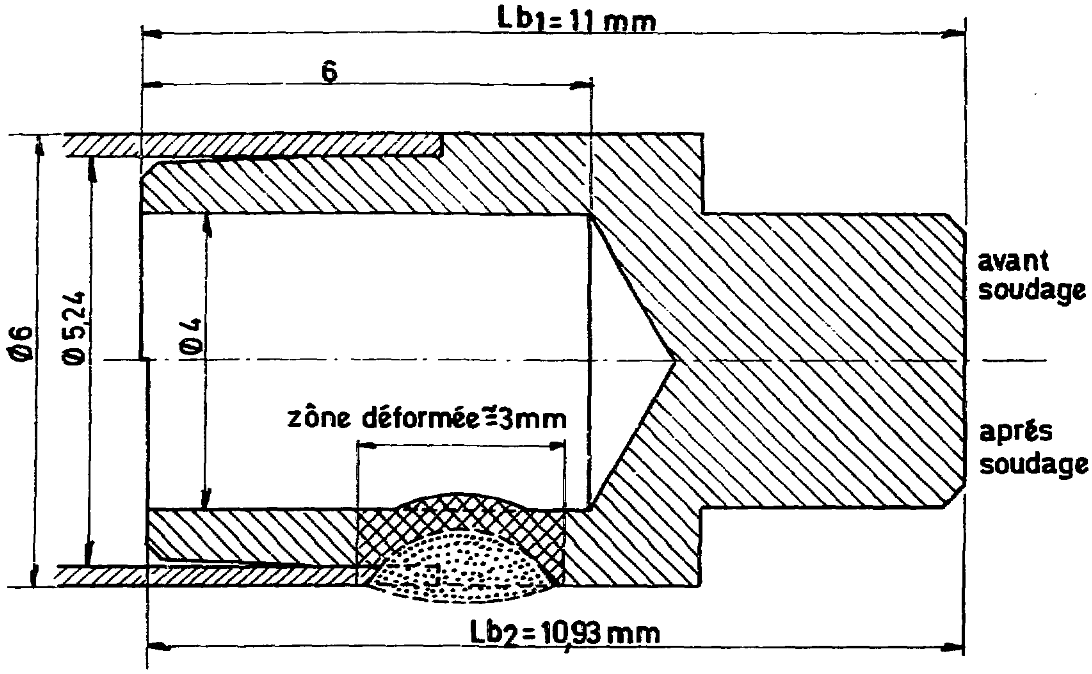

Fig 5A. MESURE DU RETRAIT D'UN BOUCHON ALESE

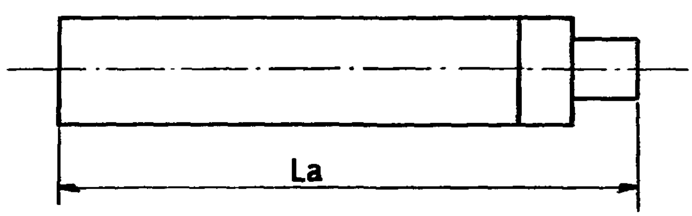

Fig 5B. MESURE DU RETRAIT

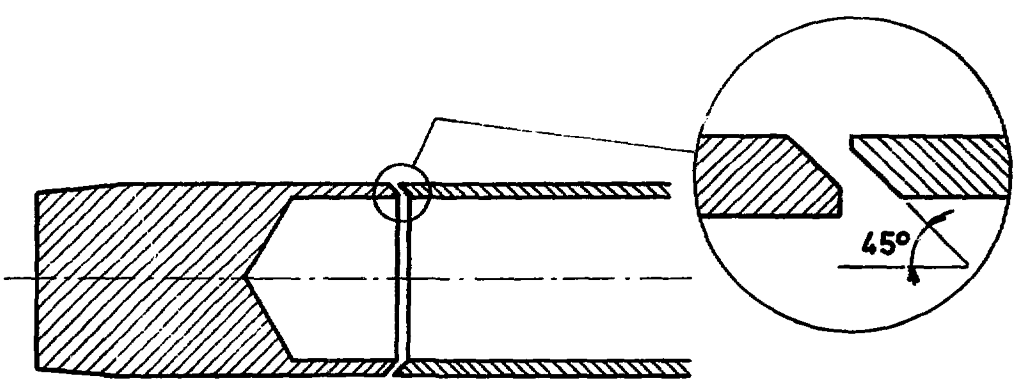

Fig 6. SOUDURE EN BOUT A ACCOSTAGE CONIQUE