Design optimisation problems of stress corrosion in welded joints in 7000 alloy

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Abstract

The use of thick plates of high-strength aluminium alloys, in specific welded structures, gives the designer many optimisation problems concerning the prediction and elimination of brittle fracture in the welded joints, caused by stress corrosion in the zone next to the weld beads. The Istituto Sperimentale dei Metalli Leggeri has faced and worked out these problems, in parallel with investigations of a metallurgical nature concerning the microstructural characteristics of the base metal in the heat affected zone (HAZ) next to the weld.
The results of these studies enabled us to define, with the aid of appropriate structural calculation techniques, some design schemes which ensure a high resistance to brittle fracture by stress corrosion in special welded joints.
This paper investigates and discusses such problems.

Riassunto

Problemi di ottimizzazione progettuale della tensocorrosione in giunti saldati in lega 7000

L'impiego di piastre di grosso spessore in lega di alluminio ad alta resistenza, in particolari strutture saldate, pone al progettista notevoli problemi di ottimizzazione per quanto riguarda la previsione e l'eliminazione dei fenomeni di rottura fragile dei giunti saldati, causata dalla tensocorrosione nella zona limitrofa ai cordoni di saldatura.
Tale problematica è stata affrontata e sviluppata presso l'Istituto Sperimentale dei Metalli Leggeri, parallelamente alle indagini di tipo metallurgico rivolte alla caratterizzazione microstrutturale del materiale base nella zona termicamente alterata, adiacente alle saldature.
I risultati di questi studi hanno permesso di definire, con l'ausilio di opportune tecniche di calcolo strutturale, alcuni accorgimenti progettuali che assicurano una elevata resistenza alla rottura fragile per tensocorrosione in particolari giunti saldati.
Tali problematiche vengono affrontate e discusse in questa memoria.

Introduction

One of the most interesting developments in the use of Al-Zn-Mg alloys in sectors other than that of aviation, for which they were specifically developed, concerns the adoption of very thick plates in welded structures for armour, as presented in various vehicles.
These alloys, having contents of Zn and Mg between 4 and 5% and 1 and 3% respectively, seem extremely suitable for applications of this kind, because they possess good weldability characteristics, mechanical strength, fracture toughness and impact resistance. In addition to the weldability characteristics, they may offer a remarkable recovery of the mechanical characteristics in the heat-affected zone next to the weld bead, by either natural or artificial ageing.
All these properties have encouraged many achievements, such as hulls of armoured vehicles, which have provided decidedly good results from the viewpoint of the weight/performance ratio.
Nevertheless, these alloys present a number of problems connected with brittle fracture phenomena due to stress corrosion which, if not adequately tackled, could restrict a wide application.

Premature fracture by stress corrosion

From a general point of view, in a welded component in 7000 alloy, made with very thick plates, three types of rupture, due to stress corrosion, can be discerned (1):

- Type 1: the rupture (Fig. 1a) starts and propagates in a direction perpendicular to the thickness direction of the semi-finished product. A welded joint whose short cross section is exposed to an aggressive environment can easily succumb to stress corrosion phenomena due to residual stresses induced by the welding process (Fig. 2).
- Type 2: the rupture (Fig. 1b) starts at the surface of the plate rather than in the thickness. In this case too, the rupture is promoted by the residual stresses near the weld. Normally, this type of rupture occurs when recrystallised surface layers are present.
- Type 3: this rupture (Fig. 1c) occurs only in the welded materials and is localised in the region next to the weld bead/base metal interface (Fig. 2).
  The crack initiates in the upper limit of the bead and propagates in the partially melted base metal of the HAZ, known as the " white zone ", whose microstructural characteristics are such as to promote a local high susceptibility to intergranular brittle fracture.
  We can consider this rupture as due to stress corrosion phenomena; it is known as " weld toe cracking " (WTC) or " boundary bead cracking ".
  The rise of WTC is once again connected with the residual stresses induced by welding, which are followed, as a rule, by those caused by the assembly process.

Brittle fracture phenomena Types 1 and 2 can be avoided by making appropriate geometric corrections to the welded structure, or by controlling the microstructure of the material with actions of metallurgical character on the production parameters.
As regards the Type 1 fracture, the exposed cross section is covered up with a continuous layer of molten weld metal; i.e. the protection generally known as " buttering " is carried out. Another way is the application of the so-called " rule of $1\frac{1}{2}t$ " (t = thickness of the plate), following which the design of

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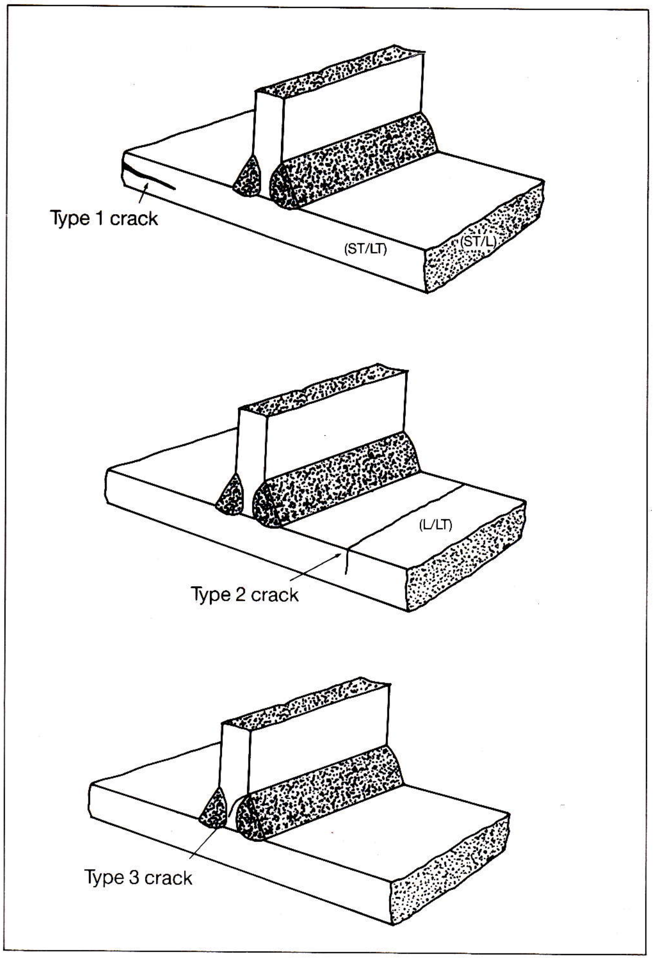
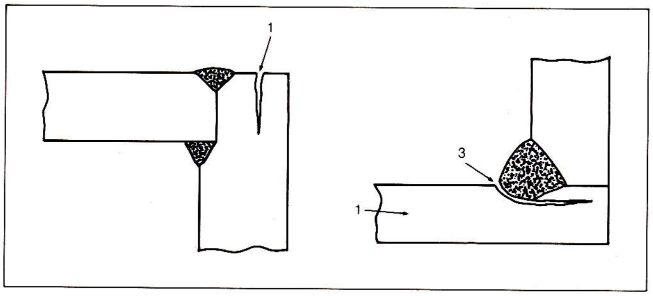


Fig. 1 - Principal types of stress corrosion cracks occurred in a welded structure made with plates of Al-Zn-Mg 7000 alloy:
a) Type 1 crack: propagates in a direction perpendicular to the plate thickness
b) Type 2 crack: propagates across the plate and perpendicular to the plate surface
c) Type 3 crack (weld toe cracking): propagates in the zone immediately adjacent to the weld bead

Fig. 2 - Schematic diagrams of the formation of cracks by stress corrosion in welded joints in 7000 alloy due to a design error (left) and to the presence of high stresses (right).



the welded structure must place the edge of the cross section at a distance from the weld bead resulting in more than 1 $\frac{1}{2}$ times the thickness of the plate near the welded zone. A third way is, of course, a design hypothesis that avoids exposing the cross section to an aggressive environment.

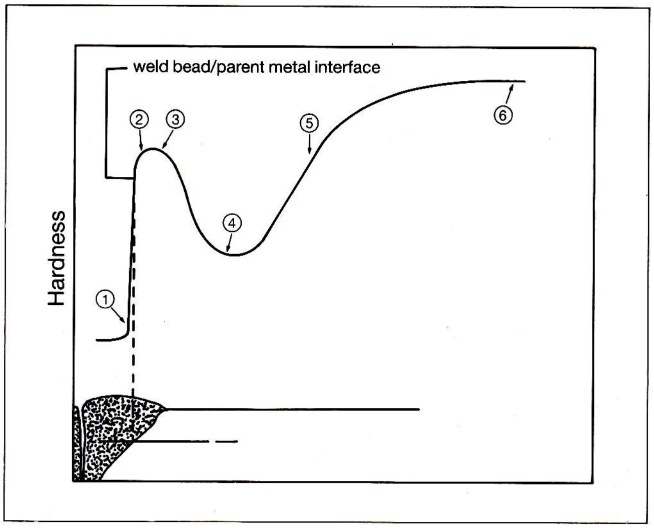
In the case of Type 2 fracture, formation of the crack can be avoided by controlling the composition of the alloy and the process parameters during production of the semi-finished product; further, the exposed surface can be treated (e.g. by shot peening) with the aim of introducing residual compressive stresses.

As regards the Type 3 fracture, the basic parameters to reduce the likelihood of rupture by stress corrosion (weld toe cracking) of a welded joint in 7000 alloy are:

- reducing the degree of local overheating in the welding operation responsible for the appearance of the "white zone";
- reducing the level of surface tensile stresses corresponding to the critical zones, due to:
  a) welding process
  b) assembly procedure
  c) service conditions
- sequence of heat treatments before and after welding.

The formation and subsequent propagation of cracks induced by stress-corrosion phenomena can have disastrous effects from the viewpoint of the mechanical integrity of the structure, and therefore the design of welded structures must pay particular attention to achieving joints in which the distribution of stresses and the geometric characteristics ensure a positive response to brittle fracture phenomena.

Fig. 3 - Schematic subdivision of the HAZ according to the hardness profile as a function of distance from the weld bead.



Structure of the heat affected zone

The heat affected zone is originated in the base metal by the thermal process of welding. The presence of a liquid front close to the weld bead, and its subsequent solidification, induce deep structural changes that partially destroy the fibrous texture of the base metal; the overheating determines the presence of a rather complex heterogeneous structure which can be divided schematically into six zones characterised by different metallurgical properties.

The gradual transition from one zone to another is emphasized by a profile of hardness as a function of distance from the weld bead (Fig. 3). The six zones identified are:

1) interface between weld bead and HAZ;
2) zone with maximum hardness recovery ("white zone");
3) transition structure between maximum recovery zone and minimum hardness recovery;
4) parts of HAZ with minimum hardness recovery;
5) transition structures between minimum hardness recovery and base metal;
6) base metal not involved in thermal phenomenon.

From the viewpoint of susceptibility to stress corrosion, zone 2 appears the most dangerous. It is characterized (2-4) by polygonal and equiaxed grains inside which the dislocations structure is greatly modified and by the appearance of liquations and segregations at grain boundary induced by the passage of a liquid front during welding.

Fig. 4 - Typical aspect of the white zone under the optical microscope: it appears as a fine white band next to the weld bead. The microhardness impressions correspond to point ② and ③ of Fig. 3. (× 100)

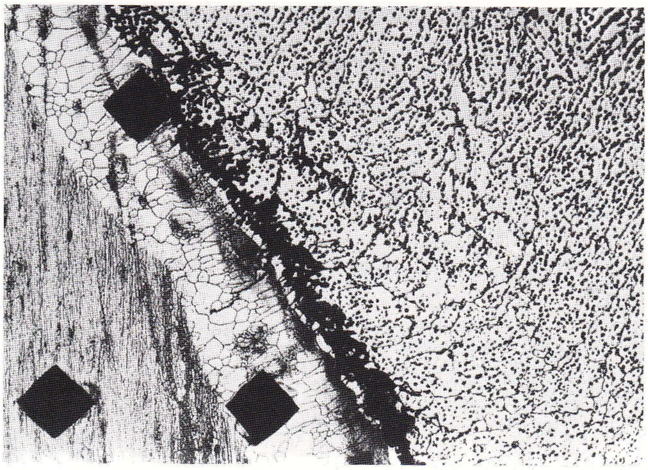


Fig. 5 - Example of brittle intergranular fracture propagating in the HAZ of a welded joint in 7020-T6/5356 alloy. (× 1000)

It is, moreover, connected with the presence of microcracks and an inhomogeneous distribution of the principal alloying elements (essentially Zn and Mg). Further, zone 2 shows a clear decrease in the density of dispersoids originating from addition elements (like Cr and Zr), whose presence greatly reduces the possibility of rupture by stress corrosion.

Under microscopic examination, this zone appears as a faint band next to the weld bead. For this reason it has been named " white zone " (WZ) (Fig. 4).

The WZ is the site of one of the most interesting and dangerous brittle fracture phenomena, the so-called " weld toe cracking " (WTC), recently studied, and attributed to an essentially stress corrosion phenomenon.

Fig. 5 shows a clear example of brittle fracture propagating in the WZ and in zones adjacent to the HAZ of a joint in 7020-T6 alloy, made by the MIG technique, using an Al-Mg alloy AA 5356 as filler metal.

Two successive figures illustrate appearances of the surface of the fracture propagating in the HAZ (Fig. 6) and in the WZ (Fig. 7).

The intergranular running is evident. The grains appear enlarged, equiaxed and their boundaries are affected by liquations.

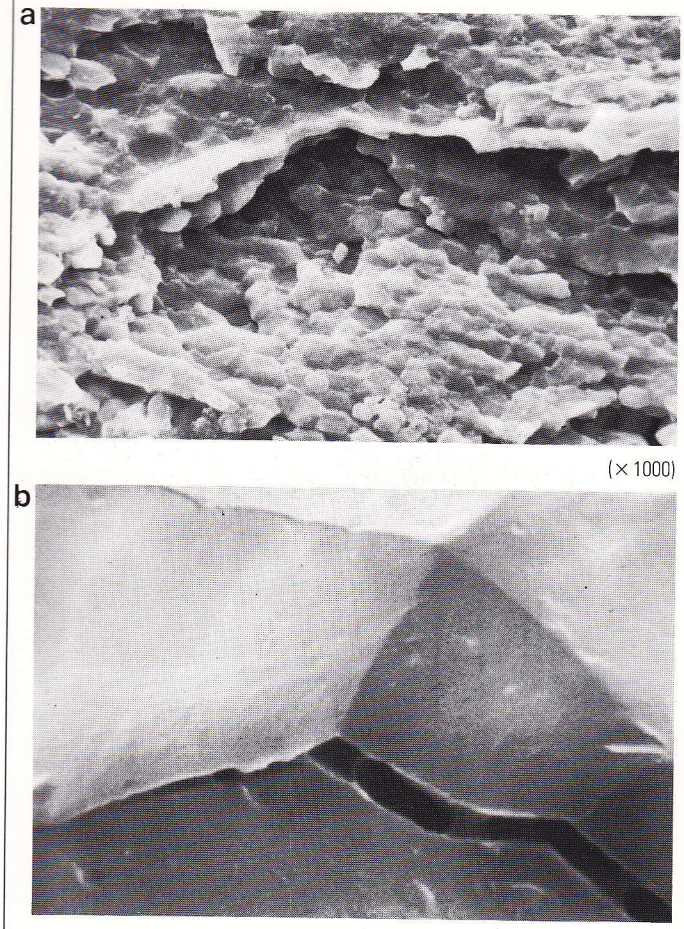


Fig. 6 - Appearance of surface fracture in the HAZ. (× 10000)

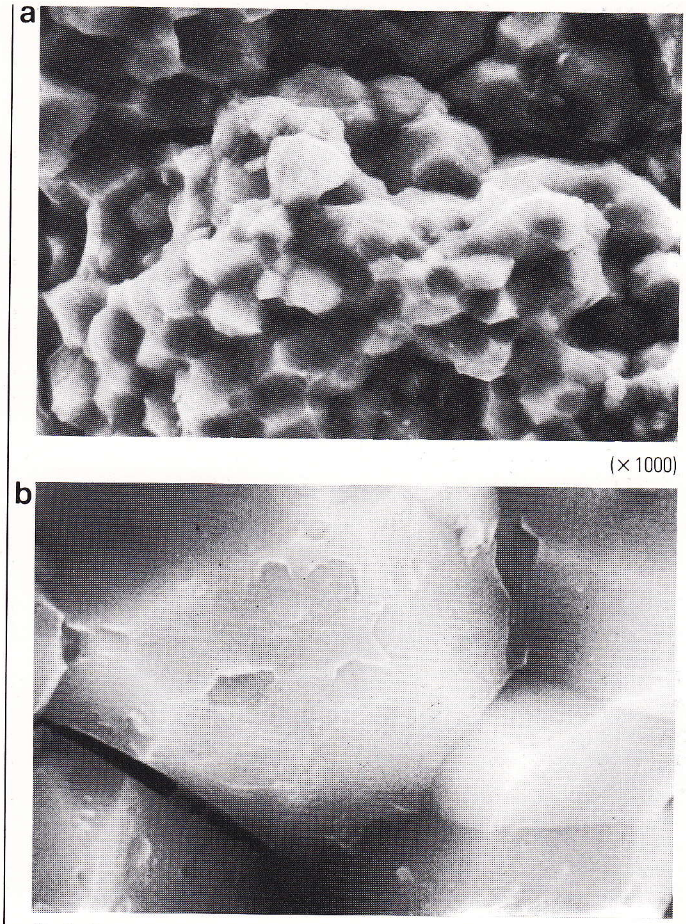


Fig. 7 - Appearance of surface fracture of the WZ. Dimples typical of ductile fracture are absent. (× 5000)

Stress distribution in the heat affected zone

Recovery of mechanical characteristics through appropriate heat treatments does not substantially improve the behaviour of the WZ in relation to stress corrosion, and propagation phenomena like that illustrated can, and must, be reduced by a careful evaluation of the stress corresponding to the HAZ.
A wide experimental work in this direction was made on an important class of welded V joints with an angle variable between 60° and 135°. Joints of this type made with 7000 alloy plates of various thickness up to a maximum of 50 mm, cover an important structural function in bodies of armoured vehicles, and the geometry of the junction node must conform to particular qualifications, demanded on one hand by ballistic protection and, on the other, by the necessity of not exposing the thickness of the plate to foreign agents.
As a result of these demands, the point of junction assumes a special aspect given by the characteristic Z-shape of the solution of continuity between plates (weld gap).
Fig. 8a shows an example of an V joint with a 120° opening in which the shape of the weld gap meets certain requirements for protection in the event of a kinetic impact directly on the weld. Moreover, it favours assembly and welding operations as regards correct positioning of the plates, while avoiding exposing the thickness to foreign agents.
The distribution of stresses in the HAZ, with particular reference to the external contour of the joint exposed to foreign agents, and therefore particularly important as regards foreseeing eventual stress-corrosion phenomena, can be determined with the aid of structural analysis techniques.

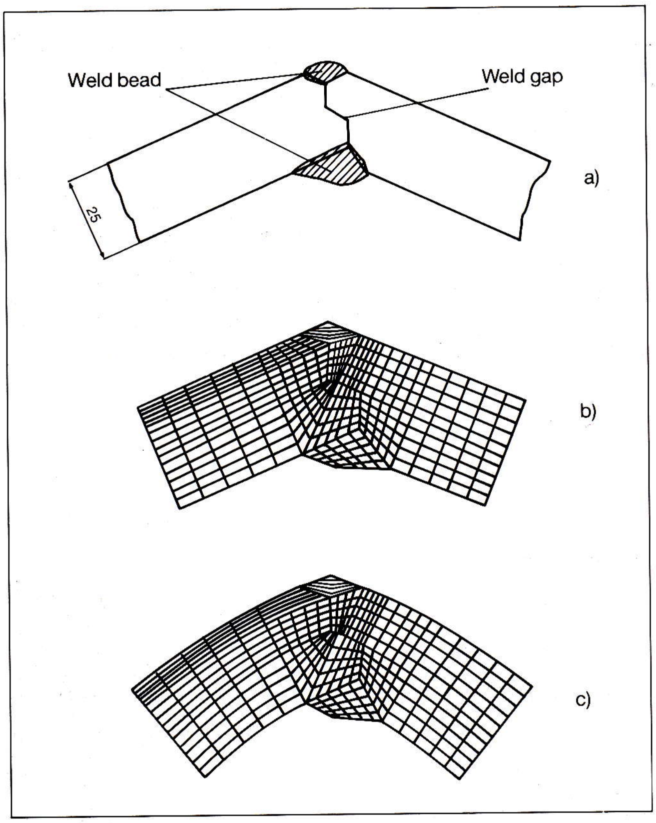
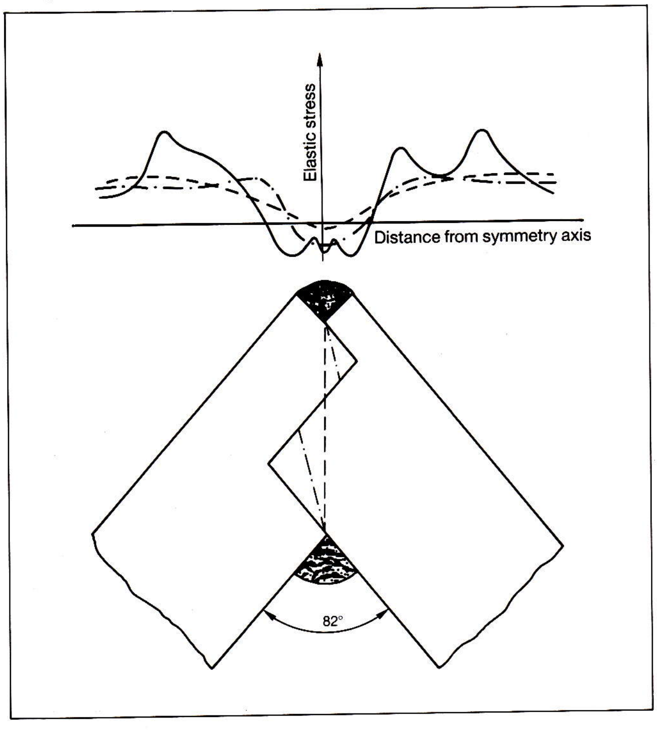


Fig. 8 - a) Example of an V shaped joint produced in 7000 alloy; the shape of the weld gap ensures ballistic protection.
b) Detail of a node of junction of structural model using finite elements to determine the stresses.
c) Appearance of a deformed node (case of elastic deformation) in a load hypothesis which tends to close the joint inwards.

Fig. 8b shows part of a plane model with finite elements used for carrying out calculations which determine the stress state in the section of the joint, in a hypothetical case of load relating to an actual situation similar to that used in industrial tests (5). In series, Fig. 8c shows the appearance of the deformed node (on the hypothesis of elastic deformation) under the effect of a load configuration which tends to close the joint (6). Numerical methods allow a quick and accurate evaluation of various design hypotheses relating to different weld-gap geometries studying both the progression of the stresses on the external contour of the joint with the aim of optimising the response to stress corrosion, and that of the stresses on the inside of the section, evaluating in the latter case whether the stress concentrations at the welding base, corresponding to the weld-gap extremities, are compatible with the service conditions.

Fig. 9 shows how three different weld-gap configurations give rise to different stress distributions on the outside contour of the joint.
In the symmetrical configuration, the stress distribution is characterised by a slight state of compression corresponding to the weld bead; also the adjacent zone is weakly stressed in tension, and associated with a gradual increase up to a maximum. In the configuration where the shortest segments of the Z-shape of the weld gap are parallel to the outer surface of the joint, thus ensuring the highest ballistic protection allowed by the mechanical machinability and assembly of the joints, the distribution of the stresses shows, the load conditions being equal, a wider compressive zone than in the previous case, and of greater intensity.
Since the weld toe cracking depends essentially on a stress-corrosion mechanism, and it is not possible with metallurgical interventions to bring the HAZ back to a microstructure comparable with that at the start, controlling the stress level remains the only possibility of avoiding premature fracture phenomena in the proximity of the weld bead.
However, experimental verification remains the final step before using a particular weld geometry.

Fig. 9 - Variations in the distribution of stresses as a function of the geometry of the weld gap in a joint welded at 82°.



Joints are made by the conventional industrial welding processes; stress-corrosion tests are then carried out through simulations of the service structures in aggressive environments.
Experimental analysis is carried out on instrumented joints on which electrical extensometers are positioned.
Fig. 10 gives the results of extensometric tests for

Fig. 10 - Results of extensometric measurements made on two joints at 82° and 135°.

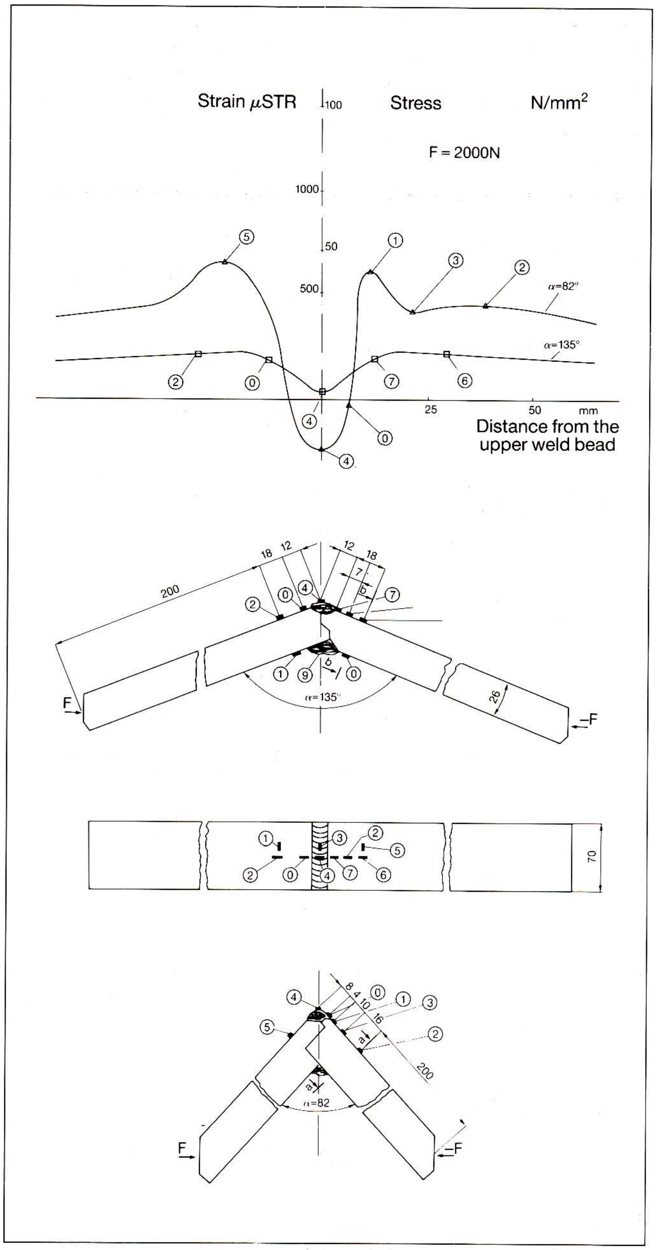


Fig. 11 - Appearance of a welded joint subjected to loading for stress corrosion test.

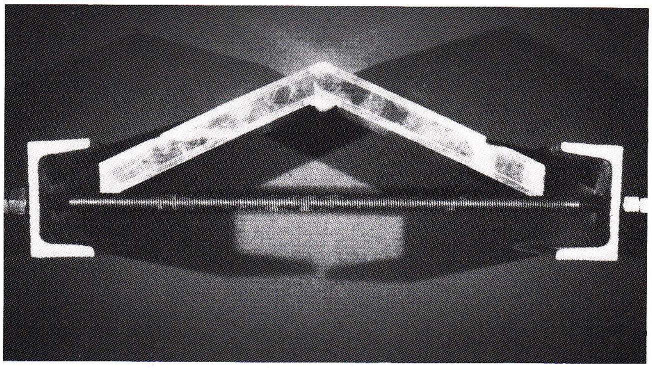
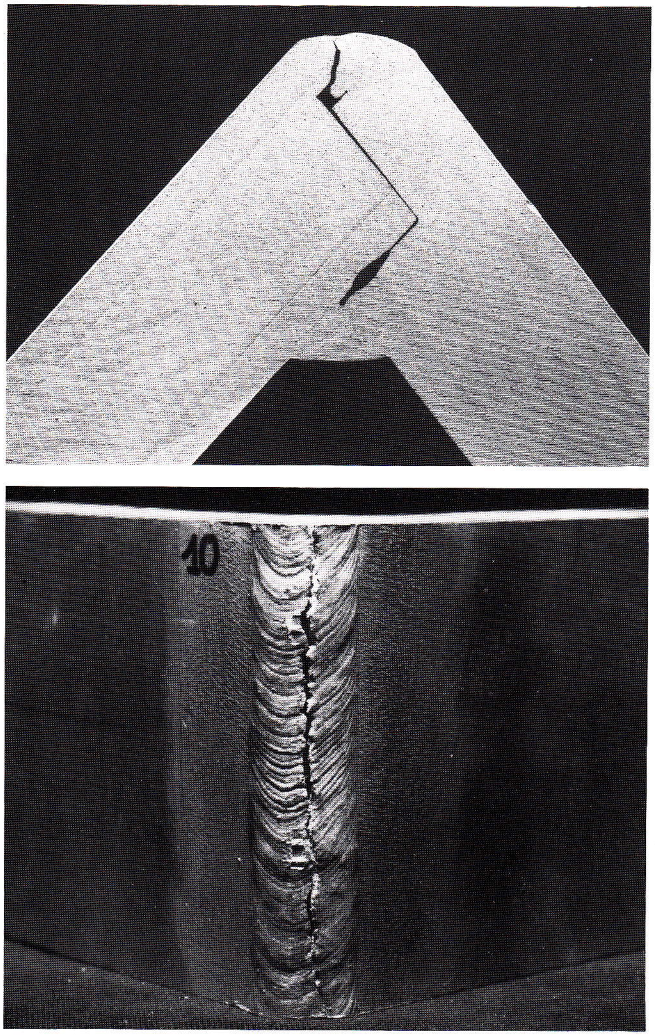


Fig. 12 - Details of a welded joint subjected to S.C. test; propagation of premature fracture by S.C. is not observed adjacent to the weld bead; the joint has been subjected to overloading during tests, and the fracture has propagated along the direction of maximum gradient of stress concentration. a) cross section; b) external surface of the joint.



determination of stresses, run on two joints of 82° and 135°; analyses of this type are of fundamental importance for confirming design analyses carried out by numerical means and for correlating the stress state with the stress corrosion response.

Fig. 11 shows a typical welded test sample subjected to stress corrosion testing in a saline atmosphere. Welded testpieces are loaded by means of steel rods, controlling the stress level with an extensometer, at a given distance from the weld bead.

Fig. 12 shows the detail of the junction node on an 82° V joint subjected to stress corrosion tests. During exposure to a saline atmosphere, premature rupture did not occur. The sample was therefore subjected to overloading and the crack propagated inside the weld bead.

Conclusions

The adoption of very thick plates of Al-Zn-Mg alloy in welded structures for armour requires a careful evaluation of the junctions geometry at the design stage.

In particular, attention should be paid to those joints in which the stress levels close to the weld bead can bring about a Type 3 brittle fracture (weld toe cracking), for which structural control alone seems able to limit the extreme danger in service, provided, of course, that the process parameters (welding conditions, assembly method) respect the optimum values. Careful laboratory tests and comparisons in service tests have confirmed these analyses, opening to Al-Zn-Mg alloys an interesting field of application.

The use of numerical methods applied to automatic calculation for studying the stress fields in the critical zones of welded joints is, moreover, a means of rapid investigation which can provide the basic information pertaining to design, avoiding long and costly experimentations.

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