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J. L. Robinson and M. H. Scott

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Liquation cracking during the welding of austenitic stainless steels and nickel alloys

By J. L. Robinson and M. H. Scott
*The Welding Institute, Abington Hall, Abington, Cambridge CB*1 6*AL, U.K.*

[Plate 1]

Liquation cracking can occur during fabrication by welding in either the heat affected zone in the parent material, or in previously deposited weld metal during a subsequent run. It results from localized melting at grain or other boundaries, combined with the thermal strains associated with welding. This review paper opens with brief descriptions of the classification, identification and mechanisms of liquation cracking. Following an outline of the material classes and circumstances in which it is most likely to occur, compositional influences in austenitic stainless steels and nickel alloys are considered in more detail. It is emphasized that although residual elements such as S, P or B may have an important role in causing or enhancing liquation effects, much liquation cracking is associated with intentional minor alloying additions, such as Nb. The influence of deliberate alloying additions, and compositional balance, in limiting the influence of residuals will be considered. In conclusion the detection, significance and avoidance of liquation cracking are discussed briefly.

1. Introduction

Liquation cracks are defects that can occur during fusion welding in either the heat affected zone (h.a.z.) in the base material or in previously deposited weld metal reheated by a subsequent weld run. In general terms they are produced by the combination of thermally induced strains arising during the welding process and very low ductility in the material being strained as a result of the local presence of an intergranular or interdendritic liquid phase. The cracks are generally small, ranging from several grain diameters to a few millimetres long at the most. Figure 1, plate 1, shows h.a.z. liquation cracking encountered during the welding of structural steel plate roll clad with an austenitic stainless steel for corrosion resistance. Figure 2, plate 1, illustrates weld metal liquation cracking in fully austenitic stainless steel multipass weld metal. In many applications it is probable that such liquation cracks have no detrimental effects on service performance, because they are so small and often sub-surface; however, in certain circumstances they may contribute to premature failure. The major economic consequence of the existence of these types of defect is that considerable effort is expended on avoiding them (particularly in weld metals), as a result both of lack of knowledge of their significance and the fact that crack-like defects are generally considered unacceptable.

The significance of this type of weldment cracking with respect to the theme of this conference is that residual elements generally play an important role in producing a susceptible material.

2. Definition of liquation cracking

The definition of liquation cracking, as one of a number of possible types of high-temperature welding crack, has been considered at length by Hemsworth *et al.* (1969) and by Hemsworth

(1970). The elements of the classification suggested by these authors is shown in figure 3. With respect to welding the chief distinction to be made is as follows. Type 1 cracks occur as a result of intergranular or interdendritic microsegregation leading to the presence of liquid films during the welding thermal cycle. Types 1B and 1C form the subject of this paper, consisting of liquation cracking in h.a.zs and weld metal respectively. The related type 1A takes the form of solidification cracking during the deposition of a run of primary weld metal. Type 2, or ductility-dip cracking, occurs at grain boundaries and is a solid state phenomenon. Types 1 and 2 may occur together, a particular case being the propagation of liquation cracks (1B or 1C) by a ductility-dip mechanism (2A or 2C). The temperature ranges in which the cracks form are illustrated in figure 4, type 1 being associated with loss of ductility in the region of the bulk solidus for the alloy concerned, and type 2 with a ductility minimum at well below this temperature.

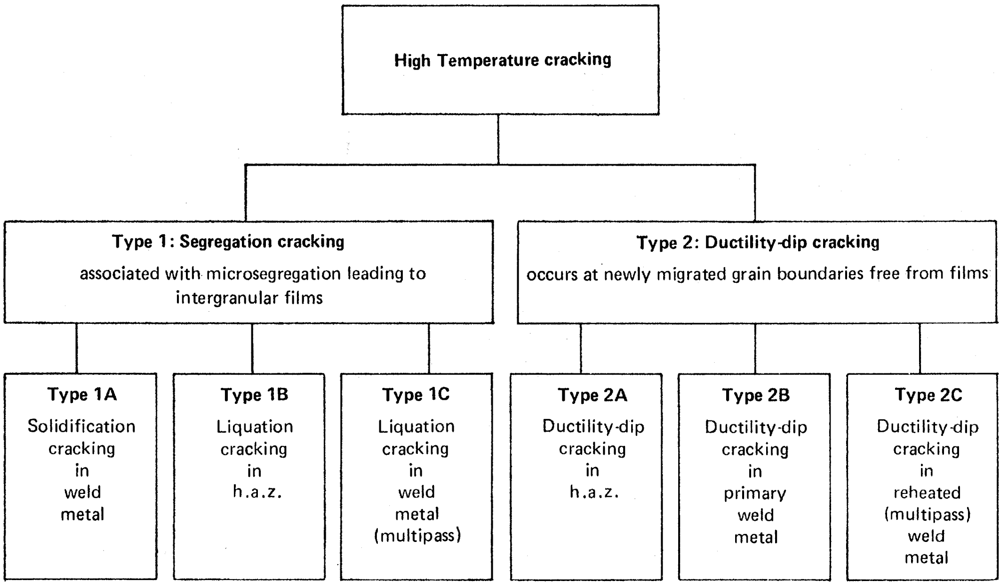


FIGURE 3. Classification of high temperature intergranular welding cracks. After Hemsworth *et al.* (1969).

With respect to the compositional factors involved in type 1, segregation cracking, a further distinction may be made depending on whether the elements segregating to the boundaries and producing liquation are deliberate alloying additions (intrinsic) or residuals (extrinsic).

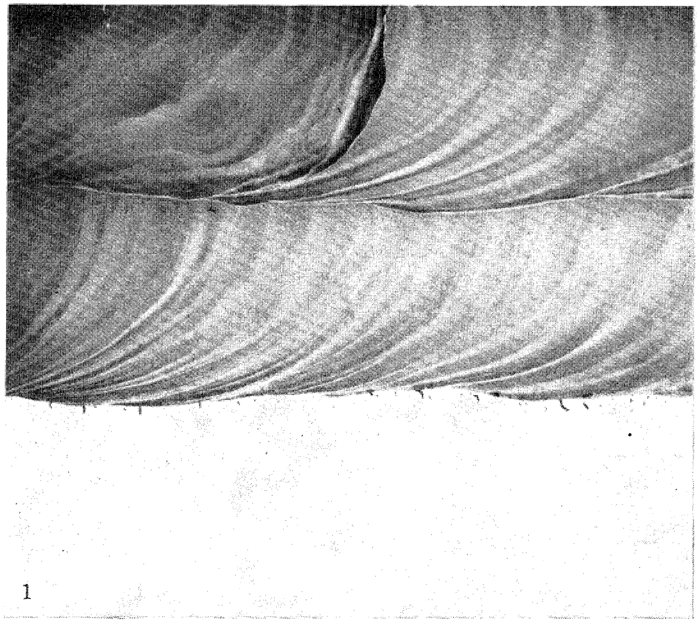
DESCRIPTION OF PLATE 1

FIGURE 1. Macrophotograph of h.a.z. liquation cracking in cladding layer of austenitic stainless steel. (Magn. × 3.8.) Nickel alloy weld metal.

FIGURE 2. Liquation cracking in austenitic stainless steel weld metal, type 316.

FIGURE 5. Heat affected zone liquation cracking in type 310 austenitic stainless steel. (Magn. × 114.)

FIGURE 6. Scanning electron micrograph of liquated film on liquation crack surface in type 316 weld metal. (Magn. × 1800.)



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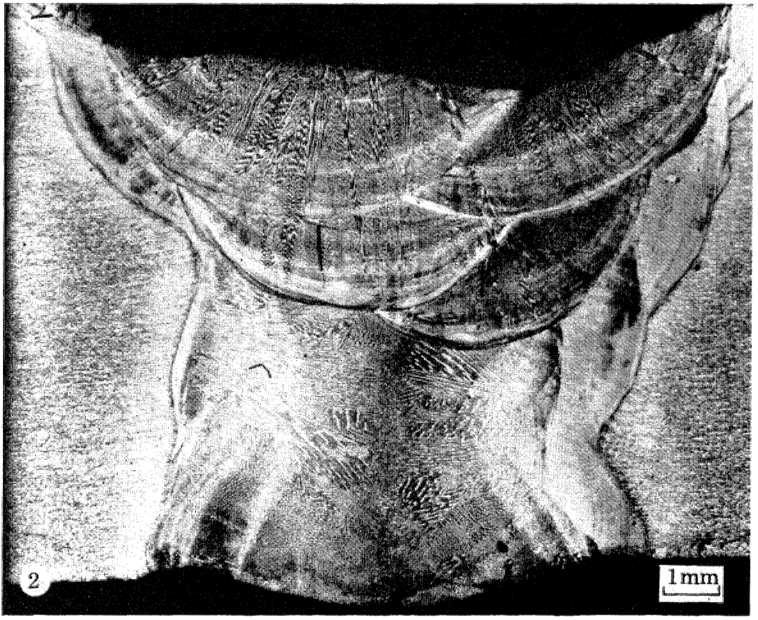

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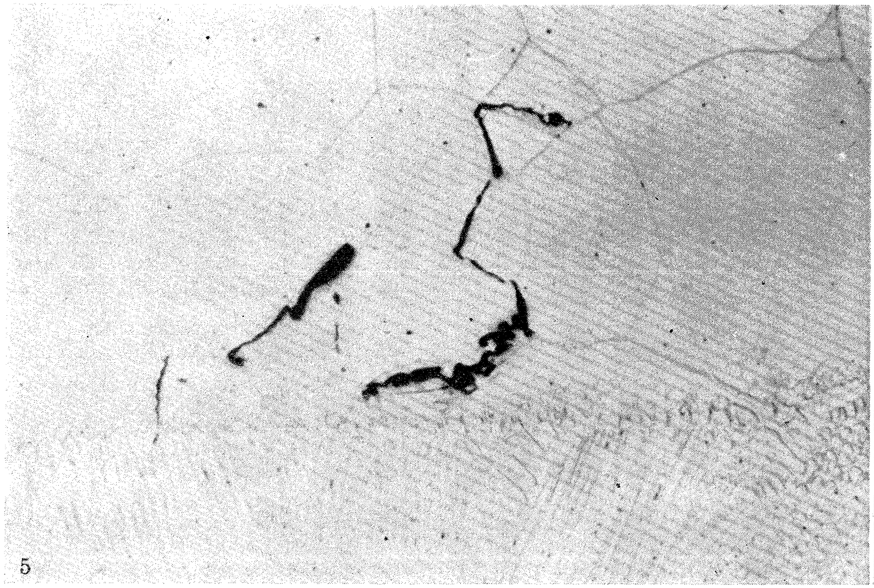

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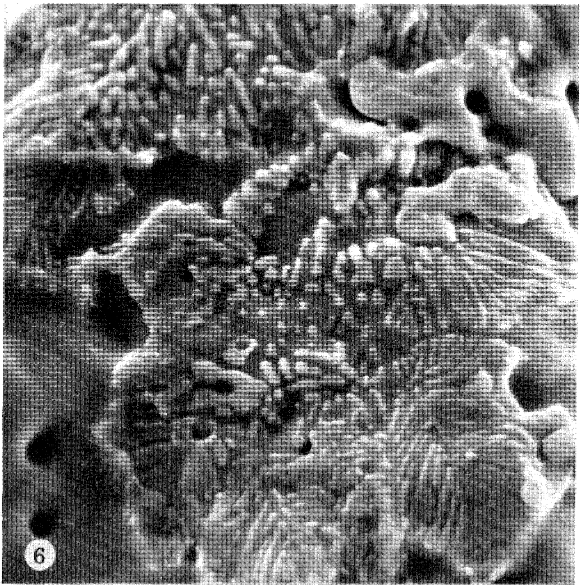

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FIGURES 1, 2, 5 AND 6. For description see opposite.

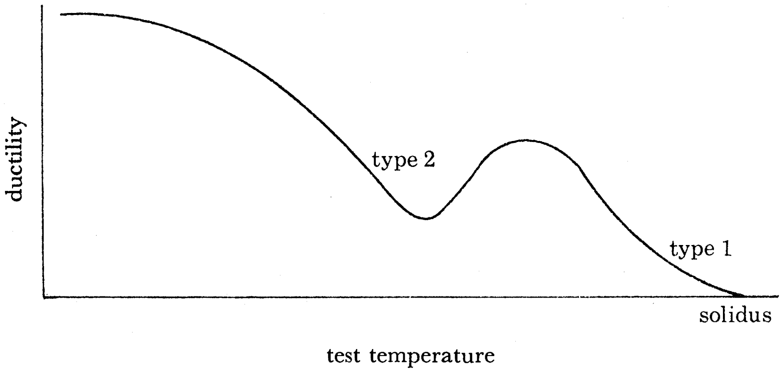

Figure 4. A schematic representation of the two temperature regions in which a ductility minimum occurs on tensile testing. Type 1 is liquation cracking, type 2 ductility dip cracking.

3. The identification of liquation cracks

This has been considered by Hemsworth *et al.* (1969) and Hemsworth (1970) in conjunction with the classification scheme outlined above. The first prerequisite for a liquation crack is its location in an appropriate place, that is in the h.a.z. adjacent to the fusion boundary or in reheated weld metal. Unambiguous differentiation between liquation (type 1) and ductility-dip (type 2) cracking may not be possible by employing optical metallography alone. Liquation cracks, particularly in the h.a.z. may display a relatively irregular and jagged path, probably corresponding to local variations in the degree of melting. An example is shown in figure 5, plate 1. Ductility-dip cracks appear relatively smooth and irregular. It should also be remembered that the two types may merge. To obtain a definitive distinction it is necessary to employ electron fractography. The distinguising feature of a liquation crack is the presence of the remains of the liquid films on the fractured surface. Morphologies may be dendritic, as illustrated in figure 6, plate 1, but this is not always so. Ductility-dip cracks will not display liquated films.

4. The mechanisms of liquation cracking

The mechanisms proposed for high-temperature weldment cracking in general and liquation cracking in particular have been reviewed by a number of authors (Borland & Younger 1960; Kammer *et al.* 1964; Hemsworth 1970). The first requirement for the formation of liquation cracks is the presence of a liquid film at boundaries during the welding thermal cycle and this has been suggested to occur in three possible ways:

(i) Preferential grain boundary melting may occur in a relatively pure alloy, particularly when solid solution coring during the original solidification of the material has extended the freezing range. This may occur with Cr and Ni in austenitic stainless steels.

(ii) Segregation of residual impurity elements or intentional alloying additions to boundaries may lower the solidus temperature. These segregates may remain either in solid solution or form a second phase.

(iii) The Rehbinder–Medovar effect consists of the migration of surface active elements along the grain boundaries into the h.a.z., with the formation of a liquid film. This mechanism does not require any segregation in the base metal.

Following the formation of liquid films, with consequently very low local tensile ductilities in either the h.a.z. or reheated weld metal, the application of a tensile strain can produce cracking. The thermally induced strains associated with the passage of a weld pool can be very complex (Chihoski 1972); however, a generalized schematic representation as regards h.a.z. liquation cracking is shown in figure 7, after Puzak *et al.* (1956). During the initial passage of the molten pool the h.a.z. material is in compression, and the presence of liquated films at this stage will not result in cracking. As the weld pool advances beyond a particular point, contraction stresses from cooling eventually result in tensile strains in the h.a.z., and if liquid films are present at this stage cracking may occur. It may thus be seen that, other things being equal, the lower the melting point of an intergranular film below that of the bulk solidus the greater will be the potential extent of cracking.

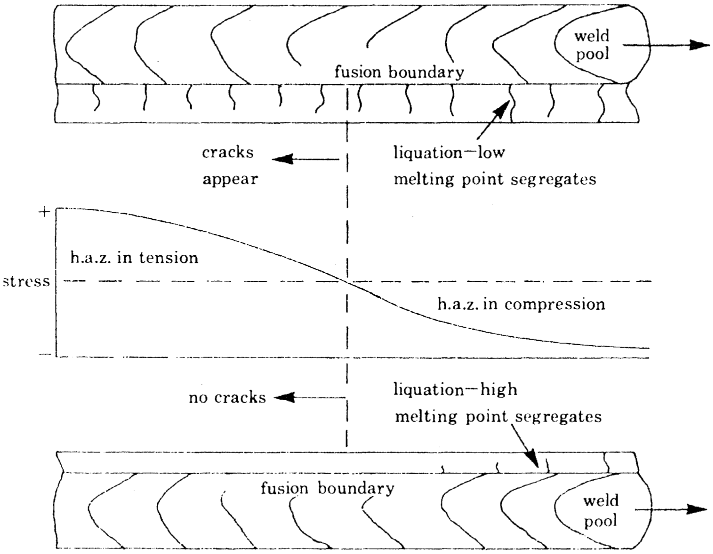

Figure 7. Schematic representation of the mechanism by which tensile stresses in the h.a.z., combined with relatively long-lived liquated films, produce cracking. After Puzak *et al.* (1956).

It is possible for healing of cracks to occur as a result of liquid metal being supplied from an adjacent reservoir, for example the weld pool. Associated with this effect is the behaviour displayed by several elements of giving rise to high liquation cracking susceptibilities only at intermediate concentrations. At low concentrations long-lived liquated films are absent, at high concentrations liquid is available to heal any cracks that form.

5. The incidence of liquation cracking

H.a.z. liquation cracking can occur in a wide range of material types, including transformable ferritic steels, austenitic stainless steels, nickel and aluminium alloys. However, as a practical welding problem it is restricted to a few specific alloy types within these general classifications or may occur when a particular factor is unusually unfavourable (e.g. grain size). When it does manifest itself it can be very difficult to circumvent. For example, the use of the creep-resistant precipitation-hardening austenitic alloy A286 (Brooks 1974; Hemsworth 1970) is severely limited in its practical application by this problem, despite a favourable combination of other properties. Although a substantial amount of literature is concerned with compositional or grain size effects, little work appears to have been done on the influence of welding process or procedure or of joint type.

(*a*) *Austenitic stainless steel weld metals*

Liquation cracking in reheated regions of austenitic weld metal may be known by a number of terms, specifically microcracking or microfissuring, and can occur in weld metals of all the 300 series stainless steels, e.g. 308 (20Cr 10Ni) and 316 (18Cr 12Ni 2.5Mo). It has been accepted for many years that the problem may be avoided by balancing the weld metal composition to retain a small proportion of the high-temperature δ-ferrite phase, typically 5–15 %, in the weld metal structure (Delong 1974) by altering the relative proportions of austenite stabilizers (e.g. Ni, C) to ferrite stabilizers (e.g. Cr, Mo). This also has the effect of lowering the susceptibility to weld-metal solidification cracking (type 1A, figure 3). Such measures are generally applied, for example, to consumables for welding the AISI wrought stainless grades 304 (18Cr 10Ni), 316 (18Cr 12Ni 2.5Mo), 321 (18Cr 9Ni+Ti), and 347 (18Cr 9Ni+Nb), and substantial attention has been devoted to determining the proportions of δ-ferrite necessary to avoid liquation cracking in these and other weld metals (Lundin *et al.* 1975). The favourable influence of δ-ferrite is generally considered to stem from two mechanisms (Castro & de Cadenet 1975). First, the solubility of a number of unfavourable residual elements, notably S and P, is substantially greater in δ-iron than in γ-iron, and the ferrite thus acts as a sink for these. Secondly, the ferrite has the effect of refining the grain size and greatly increasing the grain boundary area, thus decreasing the concentration of unfavourable segregates at any part of a boundary.

There are two areas in which this relatively convenient solution to avoiding cracking is not applicable. The first is where the compositional range of the alloy concerned is such that the δ-ferrite phase field is not readily accessible, for example the AISI 310 grade (25Cr 20Ni) which is commonly employed in heat-resistant applications. The second is where δ-ferrite is not acceptable in an austenitic weld metal as a result of property impairments produced by it (Castro & de Cadenet 1975; Gooch 1975; Stalmasek 1977).

(*b*) *Austenitic stainless steel parent materials*

H.a.z. liquation cracking may occur in the welding of all common wrought 300 series stainless steels and in cast alloys such as HK40 (25Cr 20Ni 0.4C), but can be regarded as a practical problem only in certain cases. For example, 304 or 316 rolled plate products are virtually immune, but defects of this type can occur in forgings of these alloys where very large grain sizes may be developed (Roberts & Pucknell 1967; Hemsworth 1970). The Nb-bearing 347 grade is relatively susceptible, as are some of the complex and highly alloyed austenitic stainless steels. For most grades, susceptibility is lower when the composition balance of the steel is such that a small amount of δ-ferrite forms in the h.a.z. during the welding thermal cycle (Sadowski 1974). This is also significant in the welding of castings. When the compositional type permits, these will generally contain a proportion of δ-ferrite to aid in avoiding hot tearing for much the same reasons as in weld metal. If this is not so, the frequently larger grain size and more pronounced segregation associated with a cast product may make it relatively susceptible to liquation cracking. For example, fully austenitic 347 type castings will almost always crack.

(c) *Nickel alloys*

For these materials, as in austenitic steels, liquation cracking may occur in either h.a.z. or reheated weld metal. Although Ni can be alloyed with several metals, cracking is only commonly observed in alloys containing Cr and Fe as the principal additions. Such alloys are widely used for their corrosion or oxidation resistance and/or high temperature strength. The simplest case is that of an alloy containing only Ni, Cr and Fe of which the best known example is probably Inconel 600 (Ni $15\frac{1}{2}$Cr 8Fe). To this base, alloying additions can be made that either go into solid solution or form second phases. Elements that go into solid solution, e.g. Mo and Co, give increased strength at high temperatures and, with Mo, increased corrosion resistance. Elements that form second phases, e.g. Ti and Nb, give a larger increase in strength but over a more limited temperature range where the precipitate does not overage. Depending on their intended application, such alloys may be relatively simple as in the case of Inconel 625 (Ni $21\frac{1}{2}$Cr 9Mo $3\frac{1}{2}$Nb) or complex as with Inconel 718 (Ni 19Cr 19Fe $5\frac{1}{4}$Al). All of these alloys contain residual elements such as Mn, S, Si, P and C (in some, C is present as a mandatory addition). Even more highly alloyed materials exist but they are not weldable. Most of the alloys that are weldable can be joined with filler metal of parent metal composition, and this is usually desirable on grounds of strength and corrosion. But in some cases a filler metal of different composition has to be used to reduce the susceptibility to weld metal cracking. Undoubtedly the commonest example is Inconel filler metal 82 (Ni 20Cr 3Mn $2\frac{1}{2}$Nb), which is used for welding Inconel 600. In this case the Nb addition is not intended to give increased strength but to reduce cracking, as is the Mn.

It should be mentioned that the more highly alloyed precipitation-hardened materials can also suffer from h.a.z. reheat cracking when the joint is post-weld heat-treated. This cracking occurs below the solidus (McKeown & Scott 1973) and is caused by precipitation and strain effects, not by liquation, but the distinction has not always been clear. In some cases, small weld metal cracks may also form during solidification and these are difficult to differentiate from liquation cracks. In some of the earlier papers on this subject (e.g. Bland & Owczarski 1961; Carey & McKiltrick 1962) it is not clear whether the cracks observed in welded Inconel 600 were solidification or liquation cracks. However, subsequent reports have been specific that cracks in weld metal do occur, caused by the reheating of a subsequent pass (Cordea *et al.* 1964); Yeniscavich 1966; Talento 1969), and this has also been observed by the authors. The cracking was invariably interdendritic. H.a.z. liquation cracks have been observed in arc welds (see, for example, Thompson 1969) and electron beam welds (see, for example, Bologna 1969).

6. Assessment of the risk of liquation cracking

The most direct approach is to perform actual welding tests, and this method has been the one employed almost exclusively for evaluating weld metal liquation cracking risks (Lundin *et al.* 1975, 1976). Tests of this type generally take the form of the production of a weld, or weld metal pad, followed by sectioning and metallographic examination for cracks. Tests may also take the form of making a weld run and augmenting the thermal strains associated with it by an additional mechanical strain. In the Varestraint test this is accomplished by bending the test plate by a controlled amount during welding. Materials may be ranked according to the level of augmented strain needed to produce cracks. Although direct, such techniques suffer from the disadvantages (Gooch *et al.* 1972) of requiring extensive tests and being difficult to quantify.

Particularly for evaluating h.a.z. liquation cracking risks, mechanical testing at elevated temperatures has been found to give good results (Gooch *et al.* 1972; Phillips & Jordan 1977). In this type of test a sample of the material under consideration is subject to tensile strain while undergoing a simulated weld thermal cycle. A parameter found to give generally good correlation with service experience is the interval between the temperature giving zero strength on heating and that corresponding to significant ductility recovery on cooling. In a susceptible alloy this may be over 150 °C, and typical results are shown in figure 8. Such a test conveniently lends itself to the study of factors such as grain size or variations in the welding thermal cycle.

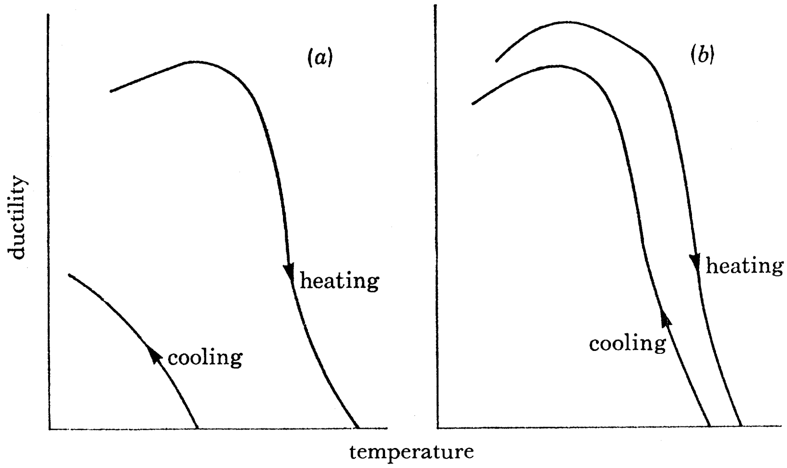

FIGURE 8. Schematic representation of hot tensile test results. (*a*) Large zero ductility interval, and high liquation cracking susceptibility. (*b*) Small zero ductility interval, and low liquation cracking susceptibility.

7. COMPOSITIONAL EFFECTS

The compositional factors found to influence liquation cracking susceptibility in both austenitic steels and nickel alloys have a number of aspects in common. First, it is generally the more complex materials, containing several alloying additions to achieve particular property combinations, in which the problem is at its most severe. In these, other metallurgical variables have to be more closely controlled to achieve good weldability, in particular fine grain sizes are required. Secondly, a variety of elements, both residuals and deliberate additions, are found to be contributing to liquation, depending on the particular alloy studied. This makes rationalization of compositional effects difficult, at least on a broad front. Thirdly, as previously mentioned, a particular element may be found to be detrimental only at intermediate levels, being harmless at low levels and acceptable at high ones. A number of studies have shown alloys made with particularly pure materials to display high liquation cracking resistance without the reasons necessarily being evident (Kireeva 1971).

Austenitic stainless steels

A number of workers have reviewed compositional influences on high temperature weld cracking in austenitic stainless steels (Hull 1960; Borland 1960; Heger 1966; Honeycombe & Gooch 1973). As pointed out by the last authors, a close parallel can be drawn between solidification cracking in the weld metal (type 1A) and liquation cracking (types 1B and 1C), and the compositional factors influencing them would be expected to be similar. This section will emphasize the major influences, with particular attention to more recent work on residual elements and the effects of minor alloying additions.

Liquation cracking may be influenced by the major elements in a particular alloy (e.g. Cr, Ni, Mo), by residual elements or by elements that may be either residuals or deliberate small alloying additions. Work has generally concentrated on the effects of one or two specific components of a system, with few systematic quantitative investigations of the interactions between them, although these are likely to be of major importance.

The ubiquitous residual elements S and P are universally accepted to increase liquation cracking susceptibility. In view of its importance to welding consumable manufacturers, especially where the weld metal must be free from δ-ferrite, attention has been paid to the maximum acceptable levels, which are generally found to be less than about 0.015 % in each case (Honeycombe & Gooch 1973). In recent work (Backman & Lundquist 1977) these limits were also found applicable to a highly alloyed austenitic steel (25Cr, 22Ni, 2Mo, 0.12N, 0.020 max. C) weld metal for urea plant applications, provided a Mn level of about 4.5 % was maintained. However, in developing crack resistant filler materials for the highly corrosion resistant austenitic alloy Carpenter 20Cb-3 (35Ni, 20Cr, 3.5Cu, 2.5Mo, + Cb), considerably lower maximum limits of 0.010 % P and 0.005 % S were found preferable (Brown & Koch 1978). As might be expected, these elements have been shown to segregate intergranularly in both weld metals (Arata *et al.* 1966; Astrom *et al.* 1976; Fredriks & van der Toorn 1968) and in h.a.zs (Edmonds & Goodwin 1976). The exact mechanisms by which this segregation induces liquation is not clear; the residuals may be present in solid solution in the austenite and lower the solidus temperature, or they may form low melting point compounds, for example MnS or Ti_2S (Egnell & May 1970).

Two minor alloying additions whose contents are in many cases adjusted with hot cracking susceptibility in mind are Mn and Si. Mn additions are generally favourable (Honeycombe & Gooch 1972) and are commonly made in amounts of 3–5 % to ferrite-free austenitic consumables, for example those for welding AISI 310 (25Cr 20Ni). The improvement of liquation resistance with increasing Mn content may be regarded as resulting at least partly from an increase in ability to combine with S and thus to prevent its migration to boundaries, although it may also result from effects on other high-temperature phase relations. Si in weld metals has the primary function of deoxidation, but its presence in amounts greater than 0.3 % (Honeycombe & Gooch 1973) leads to a rapid increase in susceptibility to liquation cracking. This may result either from its segregation to boundaries, which has been shown to occur, or from the formation of silicate films. C in both austenitic stainless steel parent materials and weld metals may have the status either of a residual or of a minor alloying addition, depending on the grade of stainless steel and its intended application. Generally speaking, it has detrimental effects up to moderate levels on liquation cracking and, from this viewpoint, should be kept low (less than 0.1 %; Honeycombe & Gooch 1973) as it would anyway in many grades of stainless steel. However, in a recent statistically based study Sadowski (1974) found C deleterious in the h.a.z. but variable in its influence on weld metal. At high levels (more than 0.3 %) its influence may again become favourable, as a result of the formation of low melting point eutectics which can promote crack healing (e.g. cast HK40, 25Cr 20Ni 0.4C). Its influence may be particularly significant when Ti or Nb are present, either as deliberate additions or residuals, and interactions between Mn, Si and C are important.

Ti and Nb are deliberate minor additions to many grades of stainless steel but may attain significant levels as residuals in others. Their influence on liquation cracking susceptibility is generally detrimental; however, in one alloy (cast CK20, 25Cr 20Ni) Ti has been found beneficial in weld metal and h.a.z. (Sadowski 1974). The same author found Nb detrimental in both h.a.z. and weld metal at a relatively low level (0.25 %) but beneficial in the weld metal at higher levels (above about 1.6 %). In AISI 321 (18Cr 8Ni + Ti) wrought stainless steel, Tamura & Watanabe (1974) concluded that the eutectic reaction between TiC and γ-Fe was responsible for the liquated films producing h.a.z. cracking. In a more complex proprietary austenitic steel (Egnell & May 1970) the liquating phase was considered to be a modified Ti_2S containing Cr, Mo, Ni and Fe. A eutectic reactions between NbC and γ-Fe was proposed to produce the liquid phase in A.I.S.I. 347 (18Cr 8Ni + Nb) by Tamura & Watanabe (1973, 1974), The use of Ta as an alternative to Nb for weld metal stabilization has been investigated by Ohmae *et al.* (1975) with favourable results in limiting crack susceptibility. This was attributed to the lower tendency of Ta to segregate to boundaries.

A number of other minor alloying additions have been suggested for improving liquation cracking resistance. B in large amounts (0.4–1 %) has been shown to give favourable results (Hemsworth 1970; Medovar 1966). This is again a case where residual amounts of the element may increase crack sensitivity (Roberts & Pucknell 1967; Brooks 1974; Donati *et al.* 1973), for example as a result of the presence of Cr or Fe borides. Rare earth metals, principally Ce, may be added to wires intended for welding consumables to aid in workability. In some cases an addition of this type may produce favourable effects in the h.a.z. with mixed results in the weld metal (Sadowski 1974; Brown & Koch 1978). Russian workers have found the joint addition of Ca and Ce to give good hot cracking resistance in h.a.z. and weld metal (Kazennov 1975; Medovar *et al.* 1976). Microanalysis showed this to result from both the combination of O_2, S and N_2 with the additions and a reduction in the grain boundary segregation of C and Nb.

With regard to the effects of dissolved gases in weld metals on liquation cracking, N_2 is of particular significance because of its strong austenite-stabilizing effect. Dissolved N_2 can be significantly influenced by welding variables and, under certain conditions, can reduce the amount of δ-ferrite in a weld metal microstructure below that adequate to prevent cracking (Long & Delong 1973), although N_2 *per se* may exert a favourable influence (Honeycombe & Gooch 1973). O_2 has been suggested as detrimental to liquation cracking resistance (Sadowski 1974) and has been demonstrated to segregate interdendritically in austenitic weld metal (Ohmae *et al.* 1975).

Nickel alloys

Factors influencing the susceptibility to liquation cracking in addition to composition have been found to include solution-treatment temperature (for precipitation hardened alloys), grain size, and linear arc energy.

The fact that for Inconel 718, the higher the temperature of solution treatment the greater the susceptibility has been agreed by several investigators (Thompson 1969, Valdez & Steinman 1969; Bologna 1969; Lucas & Jackson 1970; Gordine 1971), and there has been similar agreement that a coarse grain size is worse than a fine one (Thompson 1969; Bologna 1969; Morrison *et al.* 1969; Lucas & Jackson 1970). If susceptibility is due to lower melting-point material segregating to grain boundaries, then certainly a coarse grain size and, perhaps to a lesser extent, high solution-treatment temperature would be expected to increase the susceptibility. However, the compositional effects are less clear. Based on tensile tests at elevated temperatures, it has been found that B, C, P and S all increased the susceptibility in Hastelloy-X markedly, Mg and Si did so to a lesser extent, while Mn and Zr were beneficial (Yeniscavich & Fox 1969), whereas in a weld test it was found that, for Inconel 718, Mn, Mg and Si were all beneficial (Morrison *et al.* 1969). Also in Inconel 718 it was found that a combination of high Mn and Si gave higher susceptibility than high Mn and low Si, while low Mn and low Si gave an intermediate result (Lucas & Jackson 1970). With one exception (Gordine 1971), investigations have shown that there is evidence of segregation at grain boundaries, although there is not necessarily any difference between susceptible and non-susceptible material (Morrison *et al.* 1969) in that both may display segregation. It seems to be agreed that Nb, Mo and C increase in concentration at boundaries and Ni, Cr and Fe decrease (Thompson 1969; Valdez & Steinman 1969; Morrison *et al.* 1969; Lucas & Jackson 1970). Ti and Al have been reported as being depleted at boundaries (Thompson 1969), not being affected (along with Mn and Si) (Lucas & Jackson 1970) and segregating to them (Ti only) (Morrison *et al.* 1970). Qualitative analysis of the face of a liquation crack in Inconel 82 at the Welding Institute showed that the liquated area was richer in Nb and Mn and probably Si and leaner in Ti, Cr, Fe and Ni than the area of ductile tearing around it. However, exactly what is liquating is not clear. Metallographically, melting at carbides and borides has been observed (Duvall & Owczarski 1967; Wu & Herfert 1967) and at sulphides (Savage & Krantz 1971). It has also been suggested that a Laves phase (based on Fe_2Nb) can form at grain boundaries and liquate on welding (Thompson 1969; Valdez & Steinman 1969). Observations at the Welding Institute, admittedly limited, have revealed one case of a liquated crack face from which protruded angular particles rich in Nb, presumably carbides: these had clearly not liquated, but this does not prove or disprove either of the hypotheses mentioned.

None the less, it would seem reasonable to conclude that Nb, a minor alloying addition, can play a part in liquation cracking, although with larger additions healing effects may occur. It is also clear that residual impurities such as Si and S can also increase the susceptibility to cracking. The effect of other residual elements is not clear.

8. The detection of liquation cracks

Although liquation cracks may be fairly readily detected by the destructive method of metallographic sectioning, or during bend tests for procedure or welder approval, the same cannot be said for the non-destructive methods currently applicable to completed fabrications. Their small sizes and irregular orientations mean that in practice they are unlikely to be found by X-ray or ultrasonic examination. Careful visual examination, particularly with the aid of dye penetrants, may find cracks that intersect the surface. In the case of weld metal this implies the necessity of weld dressing before investigation.

9. The significance of liquation cracks

Although the significance of either weld metal or h.a.z. liquation cracking in the sense of the fitness for purpose of a fabrication is in many cases uncertain, and may frequently be negligible, such cracking is certainly significant with respect to the amount of effort expended in avoiding it. This stems basically from the fact that crack-like defects are generally unacceptable in engineering practice and design codes. Although perhaps not likely to be found non-destructively in a finished fabrication, they may well show up in approval tests, particularly the side bend test. Only a small amount of experimental work on the influence of liquation cracks on properties has been published. Honeycombe & Gooch (1973), working with AISI 316 and 310 steels, found them to have generally little effect on tensile, toughness, and fatigue properties of welded joints. With respect to fatigue, similar conclusions were reached by Yeniscavich (1966) for a nickel alloy. It is possible, however, that liquation cracks may influence corrosion or creep performance in certain circumstances.

Liquation cracks have definitely been implicated in the initiation of reheat cracking in 347 stainless steels (Younger & Baker 1960).

10. Avoiding liquation cracking

It should be emphasized at this point that liquation cracking, in either h.a.z. or weld metal, only presents a practical problem in a restricted number of classes of stainless steels, the adjustment of weld metal compositions to give some δ-ferrite being of particular importance here. It is probably more ubiquitous in nickel alloys. Where the compositional factors conducive to cracking are intrinsic, as in AISI 347 or A286, overall compositional balance may be altered to reduce risk. In type 310 weld metals Mn additions may be made. Where cracking is the result of extrinsic factors, purity of raw materials, etc., is evidently important. Such alterations may not be wholly successful, and in many cases it is not possible to completely avoid cracks. It should be remembered that segregation of major alloying elements, e.g. Ni, Cr, may be playing a part.

Another material variable of particular importance is grain size (Puzak *et al.* 1956; Hemsworth 1970, Lucas & Jackson 1970). Smaller grain size reduces liquation cracking, perhaps primarily by increasing grain boundary area. In parent steels, this may be controlled only during manufacture and may tip the balance between a relatively easily weldable material and one giving problems. In weld metal, grain size may to some extent be controlled by procedural factors (Honeycombe & Gooch 1973). Choice of weld metal may limit h.a.z. cracking by encouraging healing during solidification.

Little direct research on the influence of welding procedureal variables has been published. It would generally be recommended that energy input during welding be reduced to limit cracking by reducing welding current and increasing speed (Honeycombe & Gooch 1973), although the evidence on this is conflicting (Haddrill & Baker 1965; Gordine 1971). Preheat and interpass temperature, joint restraint and fit-up appear to have little influence. It may be speculated that this results from the overwhelming influence of the highest temperature components of the welding thermal cycle at the time when cracking occurs.

11. Summary and conclusions

The problem of liquation cracking in the h.a.z. or weld metal of austenitic stainless steels and nickel alloys has been reviewed. It has been shown that it may result from intentional alloying additions or impurities, or from interactions between the two. Published work on compositional factors has generally been *ad hoc*, with the intention of producing more resistant alloys or welding consumables. Attempts at quantitative prediction of cracking susceptibility from composition alone, without experimental tests, would be difficult in most practical systems, primarily because of the numerous interacting elements that could be involved. However, it may be concluded that the simpler alloys are less likely to display the problem and that low levels of residuals are generally desirable. In many cases the practical significance of liquation cracking with respect to service performance is uncertain.

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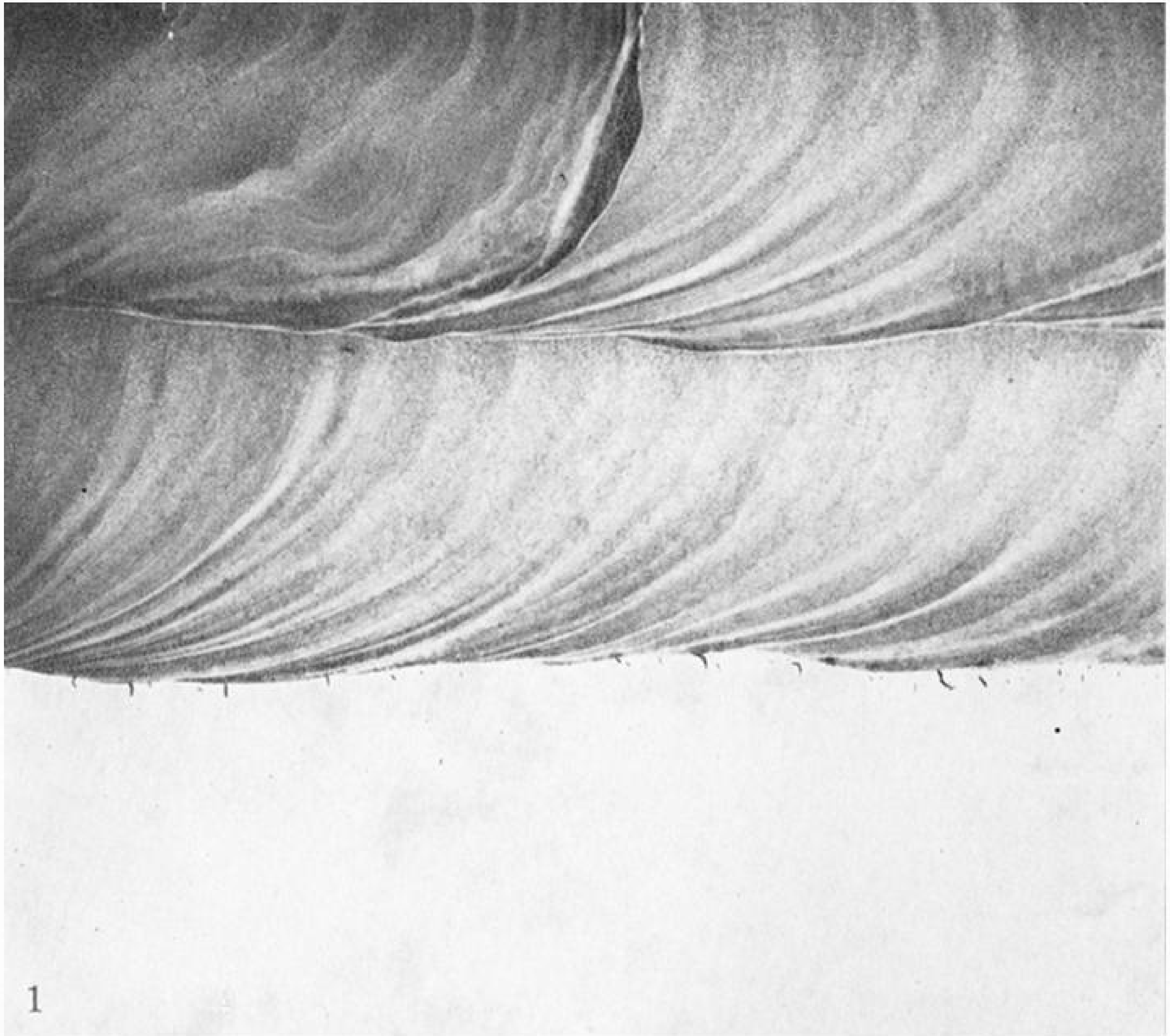
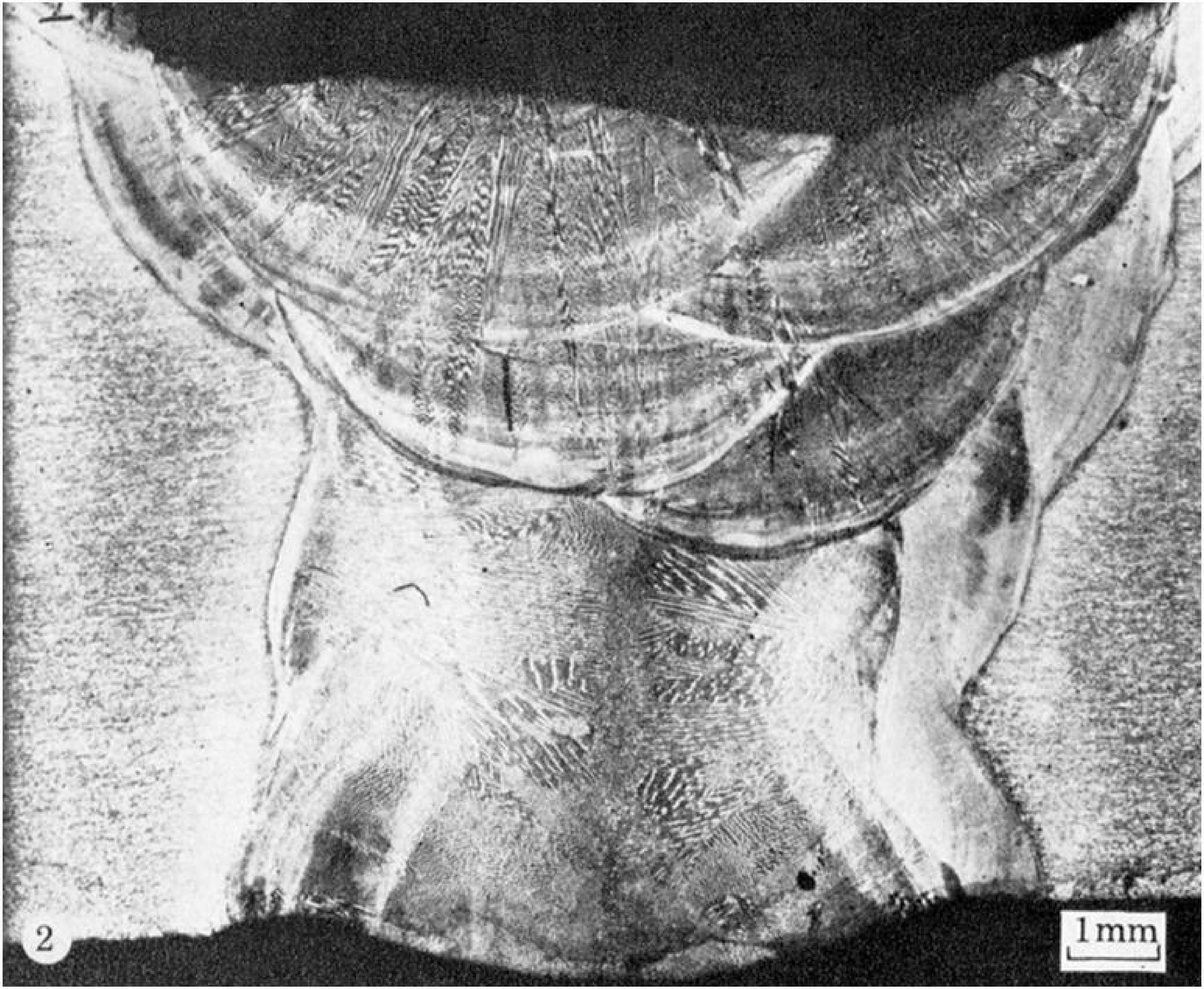


IGURE 1. Macrophotograph of h.a.z. liquation cracking in cladding layer of austenitic stainless steel. (Magn. × 3.8.) Nickel alloy weld metal.



IGURE 2. Liquation cracking in austenitic stainless steel weld metal, type 316.

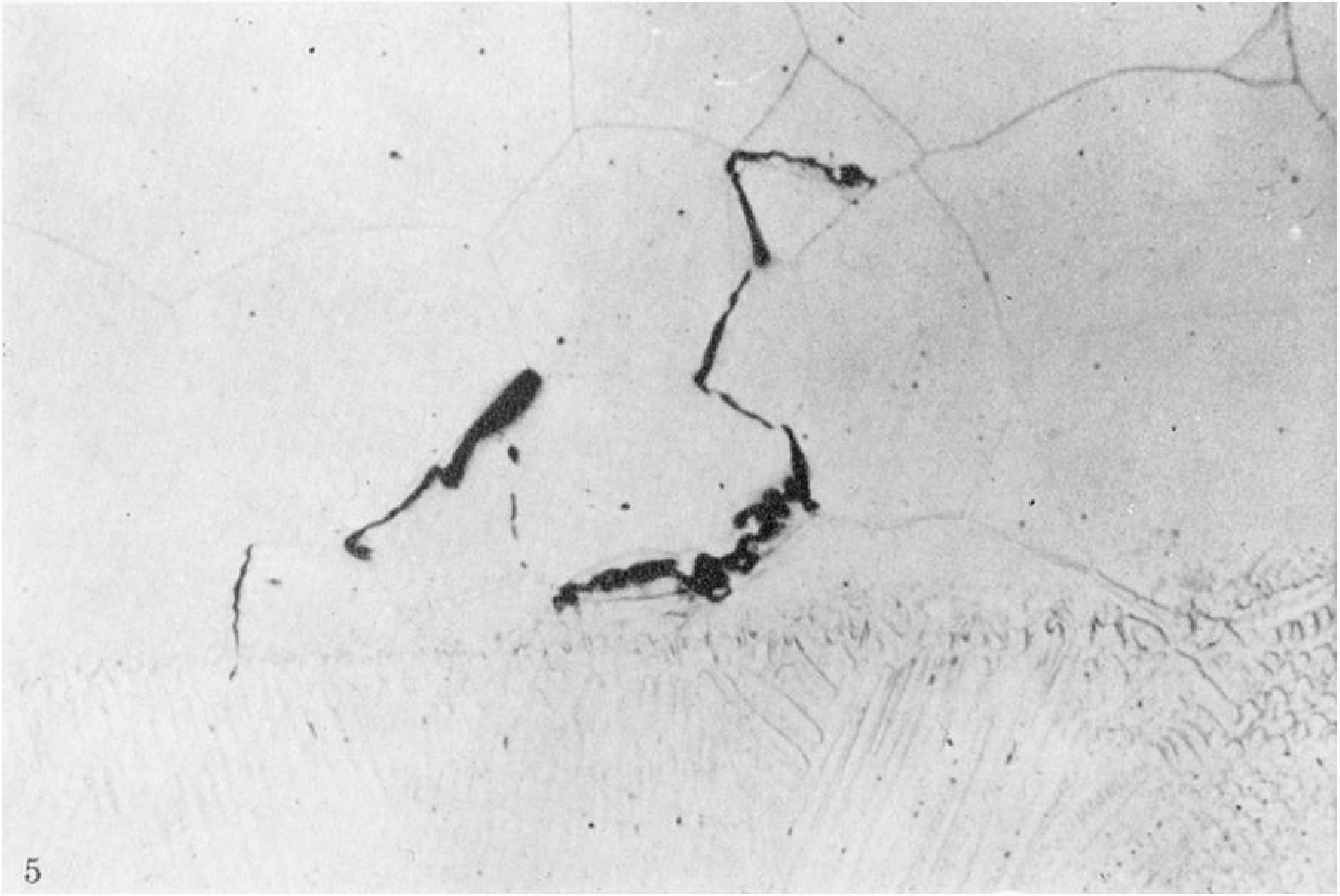
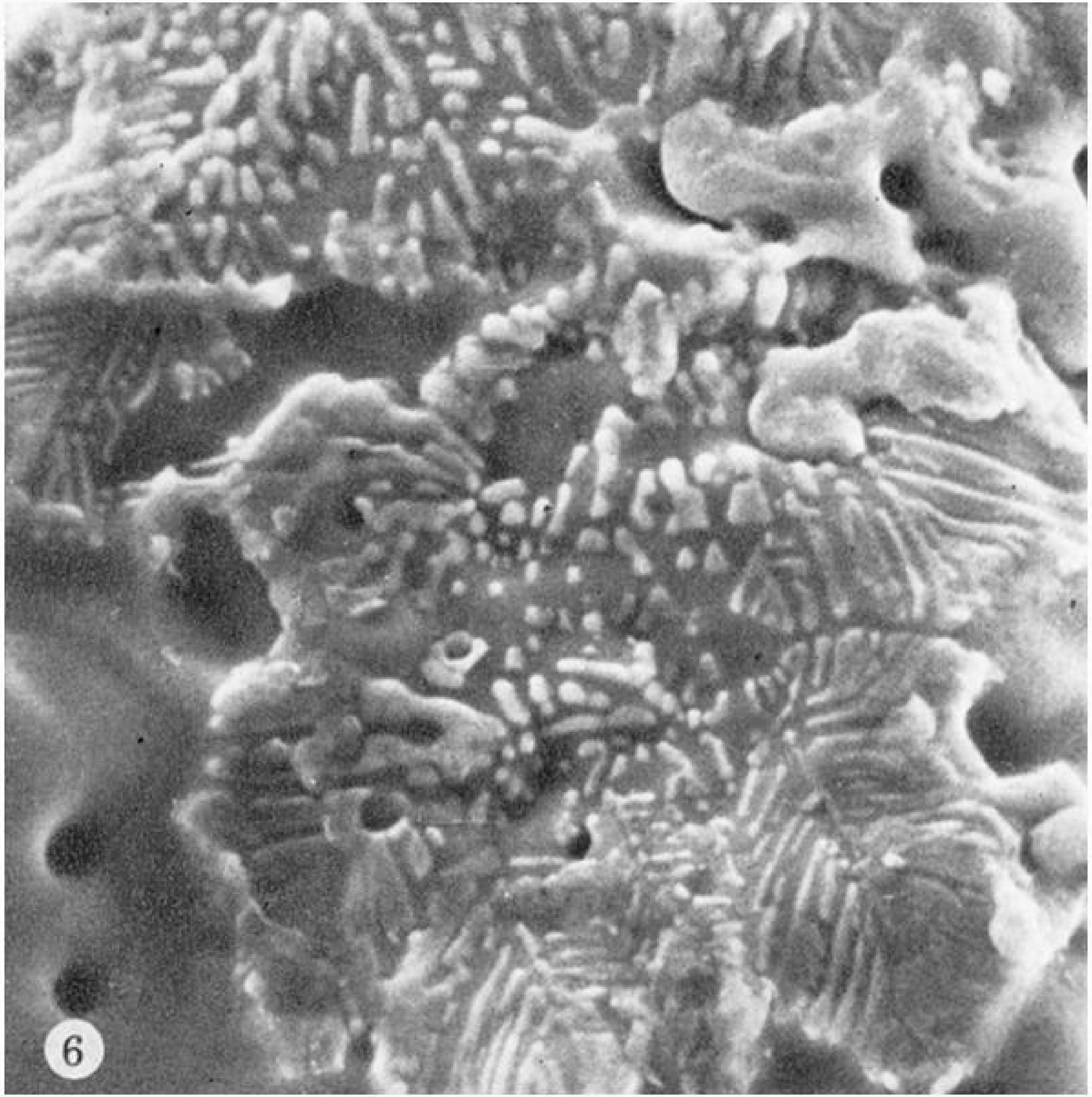


FIGURE 5. Heat affected zone liquation cracking in type austenitic stainless steel. (Magn. × 114.)



IGURE 6. Scanning electron micrograph of liquated film on liquation crack surface in type 316 weld metal. (Magn. × 1800.)