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FORMULATION AND GROWTH OF PRESENT IDEAS ON HEAT-AFFECTED-ZONE CRACKING

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PHYSICAL METALLURGY DIVISION

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FORMULATION AND GROWTH OF PRESENT IDEAS ON HEAT-AFFECTED-ZONE CRACKING

by

K. Winterton*

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ABSTRACT

Heat-affected-zone cracking is a problem in the metal-arc welding of hardenable steels. Encountered first in welding armour, the problem has persisted because high strength is now demanded in steels for many purposes.

There are four main factors responsible:

a) The hardenability of the steel, which depends on carbon and alloy content.

b) The cooling rate in the joint, which depends on heat input, thermal severity and ambient temperature.

c) The hydrogen available in the heat-affected zone, most commonly derived from moisture in the electrode covering.

d) Stresses built up in the joint because of thermal contractions.

The origins of the salient ideas about the problem have been traced among the more important contributions to an abundant literature on the subject.

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The fairly obvious dangers of heat-affected-zone cracking are dealt with briefly.

Methods of varying complexity, based mainly on the elimination of hydrogen and the control of heat input, are described for the prevention of heat-affected-zone cracking.

Direction des mines

Bulletin technique TB 99

FORMULATION ET PROPAGATION DES OPINIONS ACTUELLES SUR LA FISSURATION DUE À LA CHALEUR

par

K. Winterton*

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RÉSUMÉ

La fissuration due à la chaleur est un problème qui se pose dans le soudage à l'arc des aciers trempants. D'abord soulevé dans le soudage des armatures, ce problème subsiste à cause de la présente demande d'acier à haute résistance pour de nombreux usages.

Quatre facteurs principaux sont responsables:

a) la trempabilité de l'acier qui dépend de la teneur en carbone et en métaux alliés;

b) la vitesse de refroidissement dans les joints qui dépend de l'apport calorifique, de l'intensité de la chaleur et de la température ambiante;

c) l'hydrogène disponible dans la zone chauffée, provenant surtout de l'humidité contenue dans l'enrobage de l'électrode;

d) les tensions accumulées dans le joint à la suite de contractions thermiques.

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L'origine des idées marquantes relatives au problème a été retracée parmi les contributions les plus importantes à une abondante documentation sur le sujet. L'auteur traite brièvement des dangers les plus évidents de la fissuration due à la chaleur.

L'auteur décrit des méthodes plus ou moins complexes, de prévention de la fissuration due à la chaleur; ces méthodes sont fondées principalement sur l'élimination de l'hydrogène et le contrôle de l'apport calorifique.

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NATURE OF HEAT-AFFECTED-ZONE CRACKING

The problem of heat-affected-zone cracking arises when steels in which carbon is an important hardening or strengthening element are joined by metal-arc welding with covered electrodes. During welding, a hardenable steel has a zone, close to the weld, heated to temperatures in excess of the A_1 temperature; the metal in this zone is converted by the weld quench, partly or completely, to martensite. Cracks may develop in this zone on cooling, close to the weld junction -- so close, indeed, that to the eye it appears that they run along the junction. Microscopical examination shows that the cracks usually run parallel to the junction and about one-thousandth of an inch from it -- in fact, through the coarser grains that have received the greatest superheat.

WELDING OF TANK ARMOUR

Before 1938, information on heat-affected-zone cracking was scattered, incomplete, and sometimes erroneous.

The second World War provided a great incentive for tackling metallurgical problems, notably in the welding of tank armour, and in the period 1938-1954 great strides were made in the theory and practice of welding hardenable steels.

Mention should be made of a paper by Swinden and Reeve[1] in 1938, in which the idea of a minimum fillet size was put forward for welding alloy steels. In this paper, the weldability test now known as the Reeve test was described. This was a very massive bolted and welded assembly, in conformity with the belief at that time that restraint was necessary to cause cracking.

A further investigation on the welding of high-tensile alloy steels, sponsored by a Defence Committee, was reported by Reeve[2] in 1940. Again the Reeve test was used, and the idea of avoiding cracking by keeping the hardness in the heat-affected zone below 350 Brinell was advocated and explored. The same concept was used very successfully by Dearden and O'Neill[3] in a classical paper, also published in 1940, on the selection of alloy steels and the effect of composition on weldability.

A series of investigations[4-15] was commenced at Birmingham University in 1939. Amongst other things, it was shown[6] that heat-affected-zone cracking occurred between 94°C (200°F) and room temperature. It did not take place when the main transformation to martensite occurred, in this case in the range 345° to 205°C (650° to 400°F), as most people at that time believed. It was also found[10] that cracking occurred in a weld restrained transversely when the reaction stress built up across the weld was about 50,000 psi or even less; this stress is quite small compared with the normal strength of martensite in the heat-affected zone. A method was developed[10] to record the changing value of reaction stress across a butt weld, both while welding was in progress and afterwards until the assembly had cooled. It was found that, typically, the stress rose steeply at first and then more slowly, with a final sharp drop to zero if cracking intervened. A smaller temporary drop in the rising stress was found to be due to the transformation to martensite in the heat-affected zone. The method proved useful in studying the effect of variations in welding procedure.

It was difficult to explain why cracking should occur when the restraint was about 50,000 psi or less, since this was very low compared with the tensile strength of the hardened steel in the heat-affected zone, which would normally be expected to be in the range 200,000-250,000 psi.

It was later shown that a "tesselated" (checkerboard) pattern of local stresses exists in martensite. An X-ray technique was developed by Wheeler and Jaswon[14] to measure these stresses, and it was found that the peak values approached the yield strength of the steel in the martensitic condition.

Moreover, theoretical work[11] established that the major stress (reaction stress) and the local stresses could have an additive effect provided that the ductility was very low, approaching zero. As-quenched steels in the martensitic condition have a reputation for brittleness. However, the fact is that, in the form of tensile specimens, values of 10-15% elongation and 20-30% reduction in area are by no means uncommon in martensite.

Exceptional brittleness in the martensite of the heat-affected zone results partly from the effects of overheating[13,15]. However, another and more important key to the problem was provided by an understanding of the important role of hydrogen.

HYDROGEN AND HEAT-AFFECTED-ZONE CRACKING

As early as 1938, two German workers, Bardenheuer and Bottenberg[16], suggested that hydrogen played an important role in heat-affected-zone cracking. In the U.K., Hopkin[17-20] took this up and established it on a firm basis, the results of his work appearing in various confidential reports[17-19] from 1942 onward and later in published form[20] in 1944. Independently, in the United States, Herres[21] came to similar conclusions, which he described in a talk to the American Welding Society in October, 1943. In that talk, it was mentioned that ferritic electrodes were available with "stainless-steel type" coatings; these were apparently experimental low-hydrogen electrodes.

Rollason[22] pointed out that, in martensite formed from austenite saturated with hydrogen, cracking was likely to occur in the last stages of the martensitic transformation. Mallett and Rieppel[23] were able to prove this and confirmed the dangers of retained austenite transforming sluggishly at low temperatures. They also found that heat-affected-zone cracks could be artificially induced by diffusing hydrogen into a completed joint from which hydrogen had been excluded during the welding operation.

The introduction of low-hydrogen electrodes was a very important contribution from the United States, and these became well known in the years after the war[24]. They were slow at first to be accepted, because of the need to hold a very short arc and because of the poor bead appearance. However, the benefits that they conferred made their success inevitable. The handling characteristics have been steadily improved. Perhaps worth special mention is the introduction a few years ago of the iron-powder grades, which permit faster welding and provide weld deposits of improved appearance. Low-hydrogen electrodes, properly looked after, contain only a fraction (between one quarter and one tenth) of the moisture of ordinary electrodes. The potential hydrogen available for the heat-affected zone is correspondingly lower.

It is possible to go one step further by completely eliminating the electrode covering which gives rise to the problem. Since about 1948, when inert-gas-shielded metal-arc welding was first introduced, tungsten-inert-gas welding and metal-inert-gas welding have been increasingly used and developed. With sources of hydrogen almost eliminated, heat-affected-zone cracking is rarely encountered with these processes.

Despite the many advances that have been made possible by inert-gas welding, structural steel joining is still done almost exclusively by manual metal-arc welding, so that the problem of heat-affected-zone cracking persists.

COOLING RATE AND RESTRAINT

In the United States, the period 1941-1949 was a fertile one for fundamental studies related to the problem of heat-affected-zone cracking. Kinzel[(25)], in 1941, perhaps influenced by Reeve's work in England, proposed a scheme for controlling weldability by adjustment of cooling rates to limit the hardness in the heat-affected zone. This was taken up by Stout and others[(26-31)] at Lehigh University, under the general aegis of the Welding Research Council. Related researches were conducted at other centres. End-quench-hardenability bars and weldability tests were used in studies made at the Battelle

Memorial Institute[33-43], the Naval Research Laboratory, Washington[44-51], and the Massachussetts Institute of Technology, as well as at Lehigh University. Experimental studies were made of actual cooling rates at Rensselaer Polytechnic Institute by Nippes and others[52-58]; this was later (about 1949) to lead to the development of the Gleeble[59], a machine for simulating weld thermal cycles and assessing their effect. These experimental studies were augmented by the elegant mathematical work of Rosenthal[60,61] at the Massachussetts Institute of Technology. A useful summary[62] was made of the work done in various U.S. organizations under the general auspices of the Welding Research Council in the period 1941-1949.

At the British Welding Research Association, in the period 1946-1954, Cottrell and others[63-90] did a great deal of work on the effect of cooling rate and restraint on the incidence of heat-affected-zone cracking.

It was found that the effect of cooling rate was not uniform, but that, if a certain cooling rate was exceeded, cracking appeared. The transition was always sudden. This gave rise to the important concept of a critical cooling rate[66]. For example, in the case of a manganese-molybdenum structural steel, and using rutile-coated electrodes, the critical cooling rate was found to be 6°C per second at 300°C (10.8°F per second at 570°F).

Cottrell was only concerned with cooling rates measured at 300°C (570°F), because he found that this parameter gave the best correlation with the incidence of cracking. Other workers have measured cooling rates at other temperatures. The temperature chosen is not of great importance, provided that the general shape of the cooling rate curves remains the same, as is often the case.

Another valuable concept that appeared was that of thermal severity to describe the cooling effect of a given joint configuration(66-68). Quantitatively, the thermal severity number (TSN) signifies the sum of the thicknesses, in 1/4-in. units, of the individual plate members that form the joint. For example, the thermal severity number for a 1/4-in. butt weld is 2, and the thermal severity number for a 1/2-in. cruciform weld is 8. It was shown that the rate of cooling is proportional to the square of the thermal severity number, so that if the value of the latter increased from 2 to 8 the cooling rate is doubled.

An important finding* of Cottrell's work was that restraint had no influence in causing cracking(66); stress could open up a crack once formed, but the incidence of cracking depended solely upon cooling rate. Arising from this, the Controlled Thermal Severity (C.T.S.) test was developed(67,68,71);

*It is now believed that this is true only when excess hydrogen is available. Ordinary rutile-covered electrodes were used in Cottrell's earlier work that led to this finding.

this was a simplified Reeve test, with two anchor welds and a bolt to keep the two plates in good thermal contact. Two test welds were put in, one bithermal, with two paths for heat flow, and the other trithermal, with three paths for heat flow. To assess the weldability of a given steel, it was proposed[68,71,83,84] that the test should be done on a graduated series of plate thicknesses and the steel should be assigned a weldability index letter determined from the TSN at which cracking was first encountered. In a continuation of the work, the weldability of a number of steels was examined in depth using these concepts, including some individual steels[73,77,80,85,86,87,90] and a series of nickel-chromium-molybdenum steels[64,81]. Analysis of the data led to the basic composition for QT35, the U.K. equivalent of HY80[72,85]. A useful technique for theoretical study, devised by Cottrell[69,70,74], consisted in examining the properties of steel specimens charged with hydrogen and subjected to simulated weld thermal cycles. A summary[89] is available of the work done by Cottrell and co-workers in the period 1946-1956.

The intensive study of heat-affected-zone cracking during the war years and those that followed is illustrated by the introduction of numerous tests for susceptibility to heat-affected-zone cracking. Following the Reeve test[1] in 1938, came the circular-patch test[91,92] in 1943-44, the bead-on-plate test[38,49] in 1945, the Lehigh restrained-butt test[28] and the cruciform test[93] in 1946, and the C.T.S. test[67] in 1952.

About 1955, it seemed as though the problem of heat-affected-zone cracking was fully understood. However, work that followed raised some questions that have still not been fully answered.

Weiss, Ramsey and Udin[94], in 1956, found that on testing the weldability of some armour steels with low-hydrogen electrodes, cracking could be detected with the cruciform test but not with the C.T.S. test, even when the cooling rate in the latter was artificially increased to very high values. It appeared that Cottrell's theory, that restraint was unnecessary to initiate cracking, did not apply when low-hydrogen electrodes were used. With ample hydrogen present, cracking would occur once the critical cooling rate was exceeded, but with only a small amount of hydrogen available some additional stress was necessary to initiate cracking.

Work by Winterton and Nolan[95] in 1960 provided further information on this point, and also helped to explain the curious fact that cracking in the cruciform test occurs preferentially in the third of the four welds. It was argued that welds 3 and 4 were thermally more severe than welds 1 and 2, with four paths for heat flow instead of three. The suggestion was made that the third weld cracks because of the turning action of the fourth weld, after allowing some time for accumulation of hydrogen in the critical region. However, the importance of restraint in the conventional sense was questioned, i.e., prevention or hindrance of normal thermal contraction by means of a rigid assembly. It was pointed out that susceptibility to cracking does not always increase with increasing restraint; in fact, often the converse is true. For example, Bradstreet(96) in 1959 showed that if a C.T.S. test assembly was cut from one solid block instead of using two separate plates, cracking severity was reduced despite the increase in restraint. It appeared that a certain limited freedom of relative movement is necessary between the parts being joined, in order to allow a high stress to be built up.

In 1963, Sutherland(97) found that the severity of the C.T.S. test could be increased by deliberately making a gap of 1/16 in. between the test plates. Though this has not been explained, there are three factors that may be partly responsible. First, the area of the vertical leg may be slightly reduced, and this is where cracking occurs. Second, a hot-spot is introduced at the root in which a small hot crack could form that could subsequently initiate heat-affected-zone cracking. Third, enhanced stresses may result because of the heat distribution. In the normal test, it is probable that more of the heat of the test weld flows into the top plate than into that part of the bottom plate which is in contact with the top plate.

Consequently, the top plate expands into the weld metal while it is hot and plastic, thus increasing the stress which develops on cooling*. A controlled gap would ensure poor thermal contact between the test plates so that the mechanism described above can operate. This is in contrast with the normal test condition, in which an effort is made to provide close-fitting machined surfaces.

RECENT CONTRIBUTIONS

Since the war, there has been a trend towards the use of steels of ever-increasing strength. For example, the submarine steels have progressed from HY80 through HY100 to the present HY150, with a 75% increase in yield strength[99]. The designers of armoured vehicles are beginning to think of the armour as a structural material. In civil engineering, the introduction of the first quenched-and-tempered steel, T-1, started a revolution which still continues. The weldability of T-1 steel has been studied by Bradstreet[100]. Nowadays there are hundreds of high-strength structural steels, many of them used in the heat-treated condition. Not surprisingly, some new welding problems have arisen from the use of these high-strength steels.

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*Note: Some investigations[98] have been made of dimensional changes occurring in the C.T.S. test.

As an example, it was reported in 1962 by Masubuchi and Martin(101) that, in the heat-affected zone of HY80 welds, small intergranular microcracks were formed at high temperatures and could become nucleating points for subsequent macrocracks of the normal type. There had been hints of this before, but this was the first time that the phenomenon had been subjected to a formal investigation. Though the idea is now well-established, it is still not universally accepted(102). Savage and Szekeres(103) have suggested that cracking may occur in the zone between the true and the observed weld-plate junction.

An important trend in the development of high-strength weldable steels has been that increasing attention has been paid to purity and quality. In many of these materials, much lower limits are now set for sùlphur and phosphorus than would have been contemplated in the past. A similar concern has also been shown for restricting the permissible composition range for the major constituents. Primarily this trend has been found necessary in order to develop best properties in these high-strength materials, but welding and the properties of the welded joint must be included as part of the stimulus for the trend. In any case, the reduction of sulphur and phosphorus to very low levels assists in the amelioration of the microcracking problem (due to hot-shortness) which has just been mentioned.

In the past two decades, there has been a great increase in the use of inert-gas-shielded processes, especially for the higher strength materials. These include tungsten-inert-gas welding or TIG welding, and the so-called big-TIG process which permits faster welding speeds. Metal-inert-gas welding or MIG welding is even more important, and successive improvements have been made in this process aimed mainly at improving out-of-position welding: fine-wire welding, dip-transfer and short-arc welding, pulsed-arc welding, and pinch-arc welding. These processes do not normally provide an opportunity for water vapour to occur in the atmosphere of the welding arc, so that hydrogen is not then absorbed in the weld pool. However, hydrogen can be picked up from moisture condensed in the lines on humid days. Cases have been reported of hydrogen in the filler wire, resulting from pickling the wire before copper plating. Traces of rust on the wire surface have also been blamed. The difference is that with good housekeeping the inert-gas-shielded processes are hydrogen-free, whereas in metal-arc welding with covered electrodes, hydrogen is an ever-present source of trouble.

In recent years, some useful fundamental work has been in progress at the British Welding Research Association[104-110], often involving electron microscope studies[106,108,110]. It has been shown, by constant load tests on hydrogen-impregnated specimens, that the structure most susceptible to heat-affected-zone cracking is twinned martensite, and this is more likely to occur at the higher carbon levels(104,106). A bainitic structure is intermediate, and a plain martensitic structure, such as is obtained in 18%-nickel maraging steel, is least susceptible(104,106).

The weldability of various steels has been studied by means of dilatometer, constant-load rupture and weldability tests(107,108,110). In addition, an investigation was made of the role of inclusions and of the interaction between hydrogen and inclusions(109).

Burning and overheating cause embrittlement, and as long ago as 1950, Ko and Hanson(15) demonstrated indirectly that this could occur in the heat-affected zone of a weld. Direct observation of fractured surfaces with the electron microscope at the British Welding Research Association has now provided direct proof(105). Both sulphur and phosphorus can cause trouble directly. Carbon has an indirect influence in that as the carbon content increases, a higher manganese/sulphur ratio is needed to prevent trouble(105). A metallographic test has been developed for indicating the susceptibility of a given steel to overheating, burning, and hot tearing.

A long-term program[111-116] on welding at low ambient temperatures has been carried out by the Department of Energy, Mines and Resources, Canada. The main effect of low temperatures is to increase the rates of cooling above normal, though the heat-affected-zone cracking problem is fundamentally unaffected. The same might be said of investigations of delayed cracking in the heat-affected zone by Stout and others[117,118, 102] at Lehigh University. Hydrogen is necessary, and it usually appears that the delay time can be explained in terms of the time required for hydrogen to diffuse to the trouble spot at the particular test temperature. Incidentally, in Stout's investigations it was found[102] that delayed cracking was apparently unrelated to the high-temperature microcracking that others have blamed for initiating heat-affected-zone cracks.

Bradstreet[119] has shown that a number of the so-called low-hydrogen electrodes available in Canada did not meet the required low level of moisture content on receipt -- even some of those supplied in sealed cans. All of them had enough initial moisture to produce porosity at weld starts, and all of them absorbed moisture rapidly on exposure to humid conditions. Baking at 425°C (800°F) was satisfactory in reducing moisture to low levels. The longer the time of baking and the higher the temperature, the more resistant was the coating to absorption of moisture on subsequent exposure to humid atmospheres. This investigation raised interesting questions on the control of low-hydrogen electrodes generally; in particular, it suggests that electrodes should be issued for short work periods.

Baillie[120], working in Australia, published an interesting paper in 1967. He distinguishes between true underbead cracks and toe cracks. The latter clearly initiate at the toe of the weld, and run at an angle of about 45° to the weld junction. With the steel that he used, he found that underbead cracking occurred, in the C.T.S. test, only with high-hydrogen electrodes, and could be prevented by using low-hydrogen electrodes. The cracks occurred very soon after welding. Toe cracks, on the other hand, only occurred with low-hydrogen electrodes, but could be prevented by baking the electrodes at a high temperature. There was always an appreciable time delay before the initiation of cracking. Baillie[120] seems dubious about the capability of the C.T.S. test to reveal susceptibility of a steel to cold cracking when welding with low-hydrogen electrodes under extreme restraint. A new test was proposed by Baillie for revealing toe-cracks, which is like a C.T.S. test with vertical reinforcement of the bottom test plate.

A few words should be said about the contributions that have been made to the subject by the International Institute of Welding. In Commission IX, for example, one Sub-Commission is studying the susceptibility to heat-affected zone cracking in relation to the transformation characteristics of the steel[121].

Another group is classifying weldability tests. The work of Granjon is well known in the Commission, and also outside it through the normal technical publications[122]. Amongst other things, he has devised a technique of clamping together flat polished specimens, welding over them, breaking them apart, and then directly observing the progress of heat-affected cracking under the microscope. A new technique is being used in Czecho-Slovakia[123] and France[124] for examining the heat-affected zone. A small steel cylinder is inserted in a hole of the same diameter in a steel plate. Then a weld is made over it. The strength of the resultant heat-affected zone can be tested directly by applying a load to the cylindrical specimen, and the latter can also be pre-notched if necessary.

The Japanese delegation has been making increasingly effective contributions[125,126]. Their Tekken test is a simplified Lehigh test, but they claim to be able to control the type of cracking obtained,by using different joint preparations. Weld-metal cracking is obtained with a straight groove preparation, and heat-affected-zone cracking with a Y-groove. Using this test, Nakamura and Suzuki have studied the effect of hydrogen and restraint on cracking.

The U.S.S.R. delegation has contributed some original ideas and testing techniques on the role of hydrogen and on mathematical treatments of crack propagation[127,128].

In another Commission, Commission II, some very worthwhile contributions have been made in their programs to define limits for hydrogen level in low-hydrogen electrodes, to standardize methods for measuring moisture in electrodes and hydrogen in welds, and so on.

CAUSES OF HEAT-AFFECTED-ZONE CRACKING

Previous material has been arranged sequentially and may have lost simplicity. For this reason, an attempt is now made to summarize present ideas of the causes of heat-affected-zone cracking.

a) Carbon and Alloy Content

In a hardenable steel, cracking may develop in the heat-affected zone that forms adjacent to the weld as a result of the weld quench. Carbon content alone determines the absolute maximum hardness that can be obtained in martensite on quenching. However, in general terms, the more hardenable the steel the more likely it is that a hard brittle structure will be obtained in the heat-affected zone, and the more susceptible it will be to heat-affected-zone cracking. Despite the difficulty, much work is being done to develop weldable high-strength materials. It is known that a low-carbon martensitic structure is desirable[129]. Precipitation-hardening effects and heat treatment are also being exploited to achieve high strength without impairing weldability.

A rough assessment of the probable susceptibility of a given steel to heat-affected-zone cracking may be made, from its composition, by means of various formulae[130] for calculating carbon-equivalent values. Since this empirical approach takes no account of deoxidation practice, susceptibility to hot-cracking, or structural factors such as distribution of carbides, etc., it is not surprising that anomalies are encountered. It is more reliable to assess a given steel by means of weldability tests or by welding and examining simulated joints or assemblies.

Care should be exercised in utilizing available information on composition to assess weldability. Ladle analyses may be approximate. Careful examination may be necessary to find the various tolerances permitted on check analysis. The composition may vary across a given steel plate and along its length, corresponding to variations in the original ingot. It may also vary across the thickness. In a banded steel, high- and low-carbon bands alternate. An example may be cited of cracking occurring in a high-carbon band in the middle of the wall thickness of a pipe steel[131]. Under some circumstances, this could have contributed to a major failure. It is necessary, therefore, to avoid a superficial assessment of composition, and, rather, to consider the actual situation in the vicinity of the welded joint.

b) Cooling Rate

High cooling rates are common in welding. The cooling curve has a characteristic shape: starting like that of a water-quench at high temperatures, and finishing like that of an air-cool at low temperatures.

The faster the cooling rate, the more likely it is that heat-affected-zone cracking will be encountered. The factors that increase cooling rate are heavy plate thickness, high thermal severity (large number of heat-flow paths converging at a joint), low heat input (low current and voltage), small-diameter electrodes, and low ambient temperatures. Conversely, the factors that decrease cooling rate are thin plates, low thermal severity, high heat input (including preheat), and higher ambient temperatures. Higher cooling rates have two effects: they help to keep hydrogen in the joint, and they encourage the formation of harder, more brittle martensitic structures in the heat-affected zone. If the cooling rate is slowed down, by say preheating, there is time for a good deal of the available hydrogen to be lost by diffusion to the air before it can do any damage. In addition, the metallurgical structure in the heat-affected zone will be intrinsically softer and tougher.

If excessively high cooling rates are used, an anomaly may appear. Cracking may be prevented because the hydrogen is locked in the weld metal[81]. However, little reliance should be placed on this as a practical measure, because of the danger of delayed cracking.

c) Hydrogen

Solid steel can easily contain twice or three times its own volume of hydrogen. By cutting a sample of metal-arc weld metal and polishing one surface, the application of a thin film of glycerine makes it possible to see bubbles of hydrogen forming and leaving the surface[132]. In a similar way, the diffusible hydrogen in weld metal may be measured by collecting over glycerine (mercury and other liquids may be used) the gas that is evolved from a weighed sample[133].

Hydrogen can move around in steel through the crystal lattice in the form of charged atoms or ions[135]. The hydrogen ions can move through the grain, or faster along grain boundaries, or faster still on a free surface[134]. If the steel is cold-worked, causing dislocations to move, hydrogen ions can move in clusters with each dislocation[134]. The hydrogen ion by its presence distorts or stresses the lattice. Conversely, if the steel is stressed, the ion fits in more easily. Consequently, it tends to collect in stressed regions at the tips of notches or cracks. This accumulation of hydrogen makes it easier for a crack to propagate[134]. If the hydrogen does reach an outside surface, the atoms recombine to form molecules and the gas leaves the metal[134]. Similarly, in a tiny hole or cavity inside the metal, hydrogen can collect in molecular form and build up high pressures[136];

in this form, it can remain in the steel for years, being dissipated only very slowly[136]. Ductility, which is adversely affected by hydrogen, shows a gradual improvement with time after deposition[137].

In metal-arc welding, almost all the hydrogen comes from a very small amount of moisture associated with the sodium or potassium silicate used to bind the coating[138]. Other sources, much less common, include hydrogen already in the metal (especially from pickling); rust, condensed moisture, oil, etc., on the plate or filler metal surfaces[133]; condensed moisture in the linings or equipment for gas shielding; moisture in air entrained in the arc atmosphere; and so on. Experiments in which the arc atmosphere is artificially controlled are throwing further light on the transference of hydrogen from the atmosphere to the weld pool, and so into the welded joint[139-141].

Most electrodes (classifications 6010, 6012, etc.), even when carefully dried and stored in a warm oven, can have 2-4% moisture in the covering, and can yield 20-40 cc hydrogen per 100 g of weld metal[132]. On the other hand, low-hydrogen electrodes should have less than 1% moisture in the covering, and should yield no more than 10 cc hydrogen per 100 g weld metal[132]. If they are left exposed to the air they will pick up moisture[119]. Some low-hydrogen electrodes may cease to meet the minimum moisture requirements after about four hours' exposure to the air[119].

With very exacting welding requirements, it may be necessary to select a particular type of low-hydrogen electrode, specify sealed packaging, check electrodes on arrival, bake them at high temperatures, store them in a warm oven, and issue them in small quantities for limited time periods.

d) Stress

It is a common error to equate this factor with restraint. Restraint means a hindrance to the natural contractions of a cooling weld. Naturally, if this contraction is prevented, stress will be built up and there will be more danger of cracking than if the metal is allowed to contract freely. However, there are other stresses that may have to be taken into account.

Sometimes an additional stress may be superimposed by an external movement. It is believed that the fourth weld of a cruciform test exerts a stress on the third weld that is partly responsible for cracking in the latter.

It often happens that in a joint in which the component units are partially free to undergo relative movement, a higher stress may result than that which could develop under the influence of more complete restraint. Earlier, an indication was given of the way in which this effect works in the C.T.S. test. However, the effect is believed to be important in many different kinds of joint.

A very careful analysis is necessary to evaluate the significance of the factor of stress for a particular joint.

DANGERS OF HEAT-AFFECTED-ZONE CRACKING

For most structures, the worst danger is that a major failure may occur as the result of fatigue or of brittle fracture. If it is quite certain that these hazards do not exist, then it is possible that the existence of heat-affected-zone cracks might be tolerated.

There is plenty of evidence that cracks are potent stress-raisers, and dangerous from the point of view of providing initiating points for fatigue and brittle failure. This is widely understood. However, it may be of interest to cite a few examples where major failures have initiated from pre-existing heat-affected-zone cracks.

The failure of King's Bridge in 1962 in Melbourne, Australia, was both expensive and impressive[(142)]. This failure occurred when a low-loader trailer weighing 50 tons was part way across the bridge. Fracture occurred in several stages in the main girders, but always started from the toe of a transverse weld at the extremity of a stiffener on the lower flange. It was found that heat-affected-zone cracking had occurred at this location, and the Royal Commission charged with investigating the failure concluded that the brittle fractures in the girders were triggered from the heat-affected-zone cracks at the toes of the transverse welds. It was also decided that these cracks would not have been present if suitable welding practices had been used.

The case of a military bridge used for highway service in northern Canada is technically similar[143,144]. During the winter, one span of the bridge collapsed as a loaded truck passed over the bridge. It was found that the brittle fracture followed a path around the toe of a short weld. Microscopical examination showed that the structure in the heat-affected zone at this location was predominantly martensitic, and many examples of cracking were found. It was concluded that the carbon and manganese contents were a little higher than was desirable for good weldability, and that heat-affected-zone cracking had resulted from incorrect welding procedures. This cracking had initiated brittle failure, leading to partial collapse of the bridge.

Fire and explosion resulted from a service break in a high-pressure-gas transmission line[131]. A large, irregularly-shaped piece of steel was blown clear of the fire by the force of the initial explosion. This piece included a circular patch, approximately a foot in diameter, which had been attached by welding to repair a leak. The patch had been fillet-welded around its circumference to the outside of the pipe. The brittle fracture ran around the patch, causing almost complete separation.

On the fractured surface, shallow pockets were observed, which proved to be caused by heat-affected-zone cracking. Once again, the incidence of cracking was ascribed to incorrect welding procedures.

PREVENTION OF HEAT-AFFECTED-ZONE CRACKING

In a qualitative sense, the danger of heat-affected-zone cracking may be reduced in four different ways:

1. A steel might be selected of low hardenability, that is, with low carbon and low alloy contents. This cannot always be done, since the strength level (or some other property) required will impose restrictions on composition and this in turn will dictate the weldability of the steel. On the other hand, much work is being done to design steels of high strength with improved weldability. The use of heat-treatable steels makes it possible to achieve considerable increase in strength without impairing weldability. Another major method of achieving the same purpose is to utilize precipitation hardening. An example is 18%-nickel maraging*steel.

2. A second method is to reduce the hydrogen available by the use of low-hydrogen electrodes, or occasionally stainless steel electrodes, or by the use of the inert-gas-shielded welding processes.

*Maraging is derived from "martensite" and "ageing". These high 18 Ni-Co-Mo steels, after being heated to 900°F, harden and toughen as they cool and age; these properties are also affected by other minor constituents of a steel.

3. Sometimes it is possible to reduce the stresses built up in welding. The extent to which this can be done is very limited, though on occasion it is worth considering the use of techniques such as weaving, "buttering", back-step welding, variation of weld sequence, preheating, etc., from this point of view.

4. The most obvious and effective means of avoiding the incidence of heat-affected-zone cracking is to decrease the rate of cooling. This means the use of high energy input, for example by using large-diameter electrodes, or preheat. Under some circumstances, metal-arc welding may be substituted by a process characterized by a high energy input, such as submerged-arc welding, thermit welding, electroslag or electrogas welding, enclosed welding, etc.

For manual metal-arc welding, some attention has been paid to quantitative thermal-control methods, because only in this way can safety be achieved economically.

For some applications, rough quantitative rules have been drawn up for increasing the heat input to offset low ambient temperatures. In the field welding of pipelines, the first pass is most susceptible to cracking. With temperatures in the range -6.7 to 4.4°C (20 to 40°F), work at Battelle Memorial Institute[145] showed that cracking could occur around 63% of the perimeter of the pipe. However, if the second pass was laid within 5 minutes of completing the first pass, the amount of cracking could be reduced almost to zero. This practice has been made mandatory in a new Canadian code(146) for the welding of oil pipelines.

From Russia comes the suggestion that, for the welding of pipelines and reservoirs in winter, no passes should be made by manual welding longer than 3 ft before applying a covering pass(147). The corresponding distance for automatic welding would be about 20 ft. They also mention a rough rule to the effect that the heat input should be increased by 4-5% for every 10 °C (18°F) drop in temperature below normal shop temperatures(147).

An important system of control was proposed by Cottrell and Bradstreet(83,84) in 1955, based on the use of the C.T.S. test. A series of tests must be made on the steel, using different thicknesses of plate. The critical conditions of thermal severity for which cracking was just avoided, make it possible to assign a weldability index letter from A to G, A being most weldable and G least weldable. Bradstreet(88,148) took this further in 1956, when he compiled tabular data from which it was possible to decide on the minimum preheat and minimum energy input for any particular weld, knowing the weldability index of the steel, the thermal severity of the joint, and the ambient temperature. Moreover, he devised a formula for calculating the carbon equivalent of the steel, and hence the weldability index letter, from a knowledge of the chemical composition. In 1963, Bradstreet(149) revised the system and incorporated a new formula(130) for calculating carbon equivalent.

Based on these ideas, more detailed systems have been worked out for particular steels; for example, for the welding of C.S.A. G40.12 steel[150].

A generalized graphical system, apparently based on similar ideas, has been presented recently[151], but the derivation and background data on which the system is based are not supplied.

The Cottrell-Bradstreet system has been used successfully in the control of welding of military bridges. So far, it has not been used extensively elsewhere; attempts to obtain the utmost advantage from the system apparently provide control and inspection problems too complex for most fabricators. On the other hand, practice and familiarity with the system and its basic concepts, like thermal severity, make it possible to devise simple welding schedules, to recognize difficult joints, and to make important decisions about preheating. Such applications show the value of this kind of work.

REFERENCES

1. T. Swinden and L. Reeve, "Welding of High-Tensile Steels" - Trans. Inst. Welding (U.K.) 1(1), 7-24 (Jan. 1938).

2. L. Reeve, "A Summary of Reports of Investigations on Selected Types of High-Tensile Steels" - Trans. Inst. Welding (U.K.) 3(4), 177-202 (Oct. 1940).

3. J. Dearden and H. O'Neill, "A Guide to the Selection and Welding of Low-Alloy Structural Steels" - Trans. Inst. Welding (U.K.) 3(4), 203-214 (Oct. 1940).

4. E. C. Rollason, "The Arc Welding of High Tensile Alloy Steels - Part I: The Cracking Problem with Special Reference to Thermal Characteristics" - Trans. Inst. Welding (U.K.) 4(1), 3-9 (Jan. 1941); Welding J. 20(6), 266s-272s (June 1941).

5. E. C. Rollason and A. H. Cottrell, "The Arc Welding of High Tensile Alloy Steels - Part II: Base Metal Cracking" - Trans. Inst. Welding (U.K.) 4(1), 9-16 (Jan. 1941); Welding J. 20(6), 272s-280s (June 1941).

6. A. H. Cottrell, K. Winterton and P. D. Crowther, "Arc Welding of High Tensile Alloy Steels - Part III: The Effect of Delayed Cooling on Properties of Martensite; and a Magnetic Test for Determining the Transformation Temperature" - Trans. Inst. Welding (U.K.) 4(1), 17-21 (Jan. 1941); Welding J. 20(6), 280s-284s (June 1941).

7. D. Hanson, A. H. Cottrell, K. Winterton, J. A. Wheeler and P. D. Crowther, "Researches in Alloy Steel Welding - General Introduction" - Trans. Inst. Welding (U.K.) 7(2), 43-44 (Apr. 1944); Welding J. 23(11), 573s-574s (Nov. 1944).

8. D. Hanson, A. H. Cottrell, K. Winterton and P. D. Crowther, "Researches in Alloy Steel Welding - Part I: A Physical Examination of Welds Made from Austenitic Steel Electrodes" - Trans. Inst. Welding (U.K.) 7(2), 44-54 (Apr. 1944); Welding J. 23(11), 574s-584s (Nov. 1944).

9. A. H. Cottrell, "Researches in Alloy Steel Welding - Part II: A Note of the Initiation of Hardened Zone Cracks" - Trans. Inst. Welding (U.K.) 7(2), 54-56 (Apr. 1944); Welding J. 23(11), 584s-586s (Nov. 1944).

10. K. Winterton and J. A. Wheeler, "Researches in Alloy Steel Welding - Part III: A Quantitative Study of the Stress-Cycle Across Butt-Welds" - Trans. Inst. Welding (U.K.) 7(2), 56-68 (Apr. 1944); Welding J. 23(11), 586s-598s (Nov. 1944).

11. A. H. Cottrell, "Researches in Alloy Steel Welding - Part IV: A Note on the Effect of Local Stresses on Mechanical Properties" - Trans. Inst. Welding (U.K.) 7(2), 69-71 (Apr. 1944); Welding J. 23(11), 599s-601s (Nov. 1944).

12. D. Hanson, A. H. Cottrell, K. Winterton and J. A. Wheeler, "Researches in Alloy Steel Welding - Part V: The Problem of Hardened Zone Cracking" - Trans. Inst. Welding (U.K.) 7(2), 71-74 (Apr. 1944); Welding J. 23(11), 601s-604s (Nov. 1944).

13. J. A. Wheeler and V. Kondic, "Effect of Initial Heating Temperature on the Mechanical Properties of an Air-Hardened Ni-Cr-Mo Steel" - Symposium on Metallurgy of Steel Welding, 104 pp., Brit. Welding Res. Assoc. (1946).

14. J. A. Wheeler and M. A. Jaswon, "The Breadths of X-Ray Diffraction Lines from Martensite" - JISI 151, 161-167 (1947).

15. T. Ko and D. Hanson, "Grain Boundary Phenomena in Severely Heated Steel" - JISI 164, 51-62 (1950).

16. P. Bardenheuer and W. Bottenberg, "Tendency to Cracking of Cr-Mo Steels" - Mitt. Kaiser-Wilhelm Inst. für Eisenforschung 20(7), 77-86 (July 1938).

17. G. L. Hopkin, "A Suggested Cause for the Cracking of Alloy Steels on Welding" - Armament Res. Dept., Ministry of Supply Report (Mar. 1942).

18. G. L. Hopkin and E. L. Evans, "The Welding of High Alloy High Tensile Steels with Ferritic Electrodes with Controlled Hydrogen Coatings" - Armament Res. Dept., Ministry of Supply Report (Aug. 1943).

19. G. L. Hopkin, "A General Theory on the Cracking of Alloy Steels on Welding" - Armament Res. Dept., Ministry of Supply Report (Dec. 1943).

20. G. L. Hopkin, "A Suggested Cause and a General Theory for the Cracking of Alloy Steels on Welding" - Welding J. 23(11), 606s-608s (Nov. 1944).

21. S. A. Herres, "Discussion of Means for Evaluating Weldability of Alloy Steels" - Welding J. 23(1), 43s-49s (Jan. 1944).

22. E. C. Rollason, "The Influence of Hydrogen on Weldability of High Tensile Alloy Steels" - Trans. Inst. Welding (U.K.) 7(2), 74-75 (Apr. 1944); Welding J. 23(11), 604s-605s (Nov. 1944).

23. M. W. Mallett and P. J. Rieppel, "Underbead Cracking of Welds Cathodically Charged with Hydrogen" - Welding J. 29(7), 343s-347s (July 1950).

24. D. C. Smith, "Development, Properties and Usability of Low-Hydrogen Electrodes" - Welding J. 38(9), 377s-392s (Sept. 1959).

25. A. B. Kinzel, "The Specification of the Weldability of Steels" - Welding J. 20(10), 483s-491s (Oct. 1941).

26. G. E. Doan, R. D. Stout and J. H. Frye, Jr., Parts I and II: "A Tentative System for Preserving Ductility in Weldments" - Welding J. 22(7), 278s-299s (July 1943).

27. R. D. Stout et al., "Guide to Weldability of Steels" - Welding J. 22(8), 333s-352s (Aug. 1943).

28. R. D. Stout, S. S. Tör, L. J. McGeady and G. E. Doan, "Quantitative Measurement of the Cracking Tendency in Welds" - Welding J. 25(9), 522s-531s (Sept. 1946).

29. R. D. Stout, L. J. McGeady, C. P. Sun, J. F. Libsch and G. E. Doan, "Effect of Welding on Ductility and Notch Sensitivity of Some Ship Steels" - Welding J. 26(6), 335s-357s (June 1947).

30. R. D. Stout, S. S. Tör, L. J. McGeady and G. E. Doan, "Some Additional Tests on the Lehigh Restraint Specimen" - Welding J. 26(11), 673s-682s (Nov. 1947).

31. R. D. Stout and L. J. McGeady, "Notch-Sensitivity of Welded Steel Plate" - Welding J. 28(1), 1s-9s (Jan. 1949).

32. Report of Sub-Committee II, Industrial Research Division, Welding Research Committee. "Weldability of Carbon-Manganese Steels" - Welding J. 21(10), 448s-450s (Oct. 1942).

33. O. E. Harder and C. B. Voldrich, "Weldability of Carbon-Manganese Steels: Weld-Bead Hardness and Weld-Bead Bend Tests" - Welding J. 21(10), 450s-466s (Oct. 1942).

34. O. E. Harder and C. B. Voldrich, "Weld Bead Hardness Tests on Some Carbon, Nickel and Nickel-Chromium War Department Steels" - Welding J. 22(9), 441s-450s (Sept. 1943).

35. S. L. Hoyt, C. E. Sims and H. M. Banta, "Metallurgical Factors of Underbead Cracking" - Welding J. 24(8), 433s-445s (Aug. 1945).

36. C. B. Voldrich, R. W. Bennett and D. C. Martin, "Preliminary Study of the Notched-Bead Slow-Bend Test for Weldability of Steels" - Welding J. 25(2), 77s-90s (Feb. 1946).

37. M. W. Mallett, "The Water-Gas Reaction Applied to Welding Arc Atmospheres" - Welding J. 25(7), 396s-399s (July 1946).

38. M. W. Mallett and P. J. Rieppel, "Arc Atmospheres and Underbead Cracking" - Welding J. 25(11), 748s-749s (Nov. 1946).

39. C. B. Voldrich, "Cold Cracking in the Heat-Affected Zone" - Welding J. 26(3), 153s-169s (Mar. 1947).

40. C. B. Voldrich, D. C. Martin and O. E. Harder, "Notched-Bead Slow-Bend Tests of Carbon-Manganese Steels" - Welding J. 26(9), 489s-507s (Sept. 1947).

41. C. E. Sims and H. M. Banta, "Development of Weldable High-Strength Steels" - Welding J. 28(4), 178s-192s (Apr. 1949).

42. R. D. Williams, D. B. Roach, D.C. Martin and C.B. Voldrich, "The Weldability of Carbon-Manganese Steels" - Welding J. 28(7), 311s-325s (July 1949).

43. C. B. Voldrich and O. E. Harder, "Review on the Weldability of Carbon-Manganese Steels" - Welding J. 28(7), 326s-336s (July 1949).

44. C. E. Jackson and G. G. Luther, "Weldability Tests of Nickel Steel" - Welding J. 20(10), 437s-452s (Oct. 1941).

45. C. E. Jackson, M. A. Pugacz and G. G. Luther, "Weldability Tests of Carbon-Manganese Steels" - Welding J. 21(10), 477s-484s (Oct. 1942).

46. C. E. Jackson, G. G. Luther and K. E. Fritz, "Weldability Tests of Si-Mn Steels" - Welding J. 23(1), 33s-43s (Jan. 1944).

47. C. E. Jackson and G. G. Luther, "The Bead Weld Nick Bend Test for Weldability" - Welding J. 23(10), 523s-535s (Oct. 1944).

48. M. A. Pugacz, G. J. Siegel and J. O. Mack, "The Effect of Postheat in Welding Medium-Alloy Steels" - Welding J. 23(10), 536s-544s (Oct. 1944).

49. G. G. Luther, F. M. Laxar and C. E. Jackson, "Weldability of Manganese-Silicon High-Tensile Steel" - Welding J. 24(4), 245s-254s (Apr. 1945).

50. G. G. Luther, C. E. Jackson and C. E. Hartbower, "A Review and Summary of Weldability Testing Carbon and Low Alloy Steels" - Welding J. 25(7), 376s-396s (July 1946).

51. G. G. Luther, C. E. Hartbower and D. B. Roach, "Weldability of Low-Alloy High-Tensile Steel" - Welding J. 28(7), 289s-310s (July 1949).

52. W. F. Hess, "Evaluating Welded Joints" - Welding J. 20(10), 453s-458s (Oct. 1941).

53. W. F. Hess, "Effect of Cooling Rate on the Properties of Arc-Welded Joints in Carbon-Moly 0.50 Plate" - Welding J. 21(12), 608s-619s (Dec. 1942).

54. W. F. Hess, L. L. Merrill, E. F. Nippes, Jr. and A. P. Bunk, "The Measurement of Cooling Rates Associated with Arc Welding and Their Application to the Selection of Optimum Welding Conditions" - Welding J. 22(9), 377s-422s (Sept. 1943).

55. W. F. Hess, E. F. Nippes, Jr., L. L. Merrill and A. P. Bunk, "Determination of Cooling Rates of Butt and Fillet Welds as a Result of Arc Welding with Various Types of Electrode on Plain Carbon Steel" - Welding J. 23(8), 376s-391s (Aug. 1944).

56. E. F. Nippes, Jr. and W. F. Savage, "The Weldability of Ship Steels" - Welding J. 25(11), 776s-787s (Nov. 1946).

57. E. F. Nippes, Jr. and W. F. Savage, "State of Stress in Arc Welds Made Under Transverse Restraint" - Welding J. 27(7), 370s-376s (July 1948).

58. E. F. Nippes, Jr., L. L. Merrill and W. F. Savage, "Cooling Rates in Arc Welds in $\frac{1}{2}$-in. Plate" - Welding J. 28(11), 556s-564s (Nov. 1949).

59. E. F. Nippes, Jr. and W. F. Savage, "Tests of Specimens Simulating Weld Heat-Affected Zones" - Welding J. 28(11), 599s-616s (Nov. 1949).

60. D. Rosenthal, "Mathematical Theory of Heat Distribution During Welding and Cutting" - Welding J. 20(5), 220s-234s (May 1941).

61. D. Rosenthal, "An Important Contribution to the Science of Welding" - Welding J. 23(2), 92s-96s (Feb. 1944).

62. Weldability Committee of W.R.C., "This Thing Called Weldability" - Welding J. 28(7), 246s-264s (July 1949).

63. C.L.M. Cottrell, M. D. Jackson and J. G. Whitman, "Control of Cracking in the Metal-Arc Welding of High Tensile Structural Steels" - Welding Research 5(8), 201-215 (Aug. 1951).

64. J. G. Ball and C.L.M. Cottrell, "The Weldability and Mechanical Properties of a Series of Low-Alloy Steels" - JISI 169(12), 321-336 (Dec. 1951).

65. C.L.M. Cottrell and P.H.R. Lane, "Correlation of Weldability Tests with Structural Joints - Part I: Investigations with Tests of the Restrained Fillet Type" - Welding Research 6(2), 2-12 (Feb. 1952).

66. C.L.M. Cottrell and M. D. Jackson, "Correlation of Weldability Tests with Structural Joints - Part II: Investigations with Unrestrained Fillet Tests and Structural Joints" - Welding Research 6(4), 31-42 (Apr. 1952).

67. C.L.M. Cottrell, M. D. Jackson and J. G. Purchas, "Correlation of Weldability Tests with Structural Joints - Part III: Investigations with the Controlled Thermal Severity Test" - Welding Research 6(6), 50-57 (June 1952).

68. C.L.M. Cottrell, "C.T.S. Weldability Test for High-Tensile Structural Steels" - Welding Research 6(10), 89-92 (Oct. 1952).

69. C.L.M. Cottrell, "Delayed Brittle Fracture of Alloy Steel at Low Stress Levels" - Nature 170, 1079-1080 (1952).

70. C.L.M. Cottrell, "Assessment of Weldability by Rapid Dilatation Tests" - JISI 174(5), 17-24 (May 1953).

71. C.L.M. Cottrell, "Controlled Thermal Severity Cracking Test Simulates Practical Welded Joints" - Welding J. 32(6), 257s-272s (June 1953).

72. C.L.M. Cottrell, J. G. Purchas and B. J. Bradstreet, "Tests on Large Casts of Two Experimental Low-Alloy Steels" - Welding Research 7(8), 76-79 (Aug. 1953).

73. C.L.M. Cottrell and B. J. Bradstreet, "Vanadium as Replacement for Molybdenum in Low-Alloy Steels" - Brit. Welding J. 1(2), 82-86 (Feb. 1954).

74. C.L.M. Cottrell, "Effect of Hydrogen on the Continuous-Cooling Transformation Diagram for a Manganese-Molydenum Steel" - JISI 176(3), 273-282 (Mar. 1954).

75. C.L.M. Cottrell, "Hydrogen - Barrier to Welding Progress" - Brit. Welding J. 1(4), 167-176 (Apr. 1954).

76. C.L.M. Cottrell, "Weldability of Mn-Mo Steel Related to Properties of the Heat-Affected Zone" - Brit. Welding J. 1(4), 177-186 (Apr. 1954).

77. C.L.M. Cottrell, "Weldability of a B-Mo Steel Related to Properties of the Heat-Affected Zone" - Brit. Welding J. 1(7), 315-321 (July 1954).

78. C.L.M. Cottrell and B. J. Bradstreet, "Cooling Rates in Typical Arc-Welded Joints" - Brit. Welding J. 1(7), 322-326 (July 1954).

79. C.L.M. Cottrell, "Transformation Temperature of Alloy Steels Related to Weldability with Low-Hydrogen Electrodes" - Brit. Welding J. 1(9), 409-412 (Sept. 1954).

80. C.L.M. Cottrell, "Weldability of a C-Mn Steel Related to Properties of the Heat-Affected Zone" - Brit. Welding J. 2(2), 75-80 (Feb. 1955).

81. C.L.M. Cottrell, B. J. Bradstreet and T.E.M. Jones, "The Weldability and Mechanical Properties of a Series of Mn-Ni-Cr-Mo Steels" - Brit. Welding J. 2(3), 90-98 (Mar. 1955).

82. C.L.M. Cottrell, "Developments in Low-Alloy Steels for Welded Structures" - Alloy Metals Review 8(6), 2-6, (June 1955).

83. C.L.M. Cottrell and B. J. Bradstreet, "A Method for Calculating the Effect of Preheat on Weldability" - Brit. Welding J. 2(7), 305-309 (July 1955).

84. C.L.M. Cottrell and B. J. Bradstreet, "Calculations of Preheat Temperatures to Prevent Hard-Zone-Cracking in Low-Alloy Steels" - Brit. Welding J. 2(7), 310-312 (July 1955).

85. B. J. Bradstreet, "Weldability and Mechanical Properties of Two Low-Alloy Steels in the Hardened and Tempered Condition" - Brit. Welding J. 2(8), 347-350 (Aug. 1955).

86. B. J. Bradstreet and R. L. Wilkins, "Continuous Cooling Transformation Characteristics Related to Weldability of a 0.5% Carbon Steel" - Brit. Welding J. 2(12), 562-566 (Dec. 1955).

87. B. J. Bradstreet, "Continuous Cooling Transformation Diagram and Weldability of a 2½% Ni-Cr-Mo Steel" - Brit. Welding J. 3(1), 30-32 (Jan. 1956).

88. B. J. Bradstreet, "Practical Relationships Between Arc-Energy, Fillet Size and Amount of Electrode Used in Arc Welding" - Brit. Welding J. 3(2), 59-61 (Feb. 1956).

89. C.L.M. Cottrell, K. Winterton and B. J. Bradstreet, "The Weldability of High-Tensile Structural Steels" - Reprinted from Ministry of Supply Report W.R.(D) 1/55, 102 pages, British Welding Research Association (May 1956).

90. C.L.M. Cottrell and K. Winterton, "Weldability of a 3½% Ni-Cr-Mo Steel" - Brit. Welding J. 4(10), 481-484 (Oct. 1957).

91. C. B. Voldrich and R. D. Williams, "Weldability of Aircraft Structural Steels" - Welding J. 22(10), 545s-554s (Oct. 1943).

92. H. F. Tremlett, "Circular Patch Test for Weldability" - Welding 12, 440-445 and 493-500 (1944).

93. S. A. Herres and P. E. Woodward, "Welding of High-Strength Constructional Steels with Ferritic Electrodes" - Welding J. 25(10), 646s-658s (Oct. 1946).

94. S. Weiss, J. N. Ramsey and H. Udin, "Evaluation of Weld Cracking Tests on Steel Armor" - Welding J. 35(7), 348s-356s (July 1956).

95. K. Winterton and M. J. Nolan, "Factors Affecting Severity of Cruciform Test for Hardened-Zone Cracking" - Welding J. 39(2), 77s-82s (Feb. 1960).

96. B. J. Bradstreet, private communication (1959).

97. J. D. Sutherland, "Effect of a Joint Gap on Cracking in a High-Tensile C-Mn Steel" - Brit. Welding J. 10(3), 71-79 (Mar. 1962).

98. D. G. Howden, "Directional Effects in Standard C.T.S. Test Weld Assemblies" - Dept. Energy, Mines and Resources, Mines Branch, Physical Metallurgy Division, Internal Report PM-R-67-7 (Feb. 1967).

99. G. E. Grotke, "Weldability and Heat-Affected-Zone Toughness of HY-150 Steel" - Welding J. 43(6), 265s-281s (June 1964).

100. B. J. Bradstreet, "Application of the Cruciform Test to a Study of Cracking in T-1 Steel Weldments" - Welding J. 41(2), 62s-69s (Feb. 1962).

101. K. Masubuchi and D. C. Martin, "Mechanisms of Cracking in HY-80 Steel Weldments" - Welding J. 41(8), 375s-384s (Aug. 1962).

102. C. F. Meitzner and R. D. Stout, "Microcracking and Delayed Cracking in Welded Quenched and Tempered Steels" - Welding J. 31(9), 393s-400s (Sept. 1966).

103. W. F. Savage and E. S. Szekeres, "Technical Note: A Mechanism for Crack Formation in HY-80 Steel Weldments" - Welding J. 46(2), 94s-96s (Feb. 1967).

104. F. Watkinson, R. G. Baker and H. F. Tremlett, "Hydrogen Embrittlement in Relation to the Heat-Affected Zone Microstructure of Steels"- Brit. Welding J. 10(2), 54-62 (Feb. 1963).

105. T. Boniszewski and F. Watkinson, "Examination of Hot Tearing in the Weld Heat-Affected Zone of Ferritic Steels" - Brit. Welding J. 11(12), 610-619 (Dec. 1964).

106. T. Boniszewski, F. Watkinson, R. G. Baker and H. F. Tremlett, "Hydrogen Embrittlement and Heat-Affected Zone Cracking in Low-Carbon Alloy Steels with Acicular Microstructures" - Brit. Welding J. 12(1), 14-36 (Jan. 1965).

107. T. Boniszewski and R. G. Baker, "Hydrogen Embrittlement in Low-Carbon Nickel and Manganese Steels" - Brit. Welding J. 12(7), 349-362 (July 1965).

108. T. Boniszewski, "C.T.S. Weldability Tests of ½% Mo-B Experimental Steels" - Brit. Welding J. 12(12), 593-612 (Dec. 1965).

109. T. Boniszewski and Mrs. J. Moreton, "Effect of Micro-Voids and Manganese Sulphide Inclusions in Steel on Hydrogen Evolution and Embrittlement" - Brit. Welding J. 14(6), 321-336 (June 1967).

110. F. Watkinson and R. G. Baker, "Welding of Steel to B.S.968:1962 - A Dilatometric Investigation" - Brit. Welding J. 14(11), 603-613 (Nov. 1967).

111. H. J. Nichols, "Low Temperature Welding at Churchill, Manitoba, Winter 1948-49" - Investigation No. 2537, Bureau of Mines, Ottawa, Canada (May 1949).

112. S. A. Agnew, "Root Bead Welding of Structural Steel Restraint Specimens at Low Ambient Temperatures" - Dept. of Energy, Mines and Resources, Mines Branch, Research Report No. PM 222 (Sept. 1957).

113. K. Winterton, W. P. Campbell and M. J. Nolan, "Welding of Steel at Low Ambient Temperatures" - Welding Research Council, Bulletin No. 86 (Mar. 1963).

114. K. Winterton, "Welding of Structural Steels at Low Temperatures" - Polar Record, Scott Polar Research Institute, 3-12 (May 1960).

115. L. G. Girard, "Weldability of Steels at Low Ambient Temperature" - Dept. of Energy, Mines and Resources, Mines Branch, Physical Metallurgy Division, Internal Report PM-R-63-41 (Nov. 1963).

116. K. Winterton, "Welding of Steel in Cold Weather" - J. of Royal Naval Scientific Service 22(6), 361-370 (Nov. 1967).

117. E. P. Beachum, H. H. Johnson and R. D. Stout, "Hydrogen and Delayed Cracking in Steel Weldments" - Welding J. 40(4), 155s-159s (Apr. 1961).

118. C. G. Interrante and R. D. Stout, "Delayed Cracking in Steel Weldments" - Welding J. 43(3), 145s-160s (Mar. 1964).

119. B. J. Bradstreet, "Moisture Absorbtion in Low Hydrogen Electrode Coatings and Porosity in Welds" - Welding J. 43(1), 43s-48s (Jan. 1964).

120. J. G. Baillie, "Underbead and Toe Cracks" - Brit. Welding J. 14(2), 51-61 (Feb. 1967).

121. M. Granjon, "Current and Recent Investigations Into the Weldability of Steels in Relation to Their Transformation Characteristics" - Welding in the World 4(4), 234-244 (Apr. 1966).

122. M. Granjon, "Studies in Cracking and Transformation in Steels During Welding" - Welding J. 41(1), 1s-11s (Jan. 1962).

123. I. Cabelka and C. Million, "Proposal for a New Test Method for the Weldability of Steel" - International Institute of Welding, Commission IX, Doc. IX-557-67 (1967).

124. M. Granton and S. Debiez, "Contribution to the Study of Cold Cracking in Steel Welds by the Implant Method" - International Institute of Welding, Commission IX, Doc. IX-558-67 (1967).

125. H. Suzuki, M. Inagaki and H. Nakamura, "Effects of Restraint and Hydrogen on Root Cracking of High Strength Steel Welds" - International Institute of Welding, Commission IX, Doc. IX-408-64 (1964).

126. M. Watanabe, K. Satoh and S. Matsui, "Effect of Restraint on Root Cracking of Steel Welds" - International Institute of Welding, Commission IX, Doc. IX-409-64 (1964).

127. N. N. Prokhorov and E. L. Makarov, "Methods of Determining and Regulating the Capacity of Steels for Resisting Cold Cracking During Welding" - International Institute of Welding, Commission IX, Doc. IX-481-65 (1965).

128. V. V. Belov and M. K. Shorshorov, "Comparative Estimation of the Cold Crack Resistance of Steels by the Rigid Weld Specimen and IMET-4 Techniques" - International Institute of Welding, Commission IX, Doc. IX-519-66 (1966).

129. W. P. Hatch, R. E. Travis and C. E. Hartbower, "Welding Low-Carbon Martensite" - Welding J. 39(4), 141s-146s (Apr. 1960).

130. K. Winterton, "Weldability Prediction from Steel Composition to Avoid Heat-Affected Zone Cracking" - Welding J. 40(6), 253s-258s (June 1961)

131. K. Winterton, "Investigation of Pipeline Failure" - Dept. of Energy, Mines and Resources, Mines Branch Investigation Report IR 61-149 (Mar. 1962).

132. K. Winterton, "Mechanism of Micro-Cracking in Mild-Steel Welding" - Welding J. 36(10), 449s-456s (Oct. 1957).

133. K. Winterton and C.L.M. Cottrell, "Evolution of Hydrogen from Weld Metal" - Metallurgia 49(1), 3-7 (Jan. 1954).

134. E. J. Millett, "The Origin and Distribution of Hydrogen in Steel Weld Metal" - Brit. Welding J. 3(10), 497-509 (Oct. 1956).

135. R. H. Fowler and C. J. Smithells, "Hydrogen in Metals" - Proc. Royal Soc. (Series A) 160, 37-47 (1937).

136. K. Winterton, "Some Investigations of the Causes of Halo Formation" - Brit. Welding J. 2(9), 385-392 (Sept. 1955).

137. K. Winterton, "Properties of Mild Steel Weld Metal Not Revealed by the All-Weld-Metal Tensile Test" - Welding J. 40(3), 106s-109s (Mar. 1961).

138. D. C. Smith, W. G. Rinehart and K. P. Johannes, "Effect of Moisture in the Coatings of Low-Hydrogen Iron-Powder Electrodes" - Welding J. 35(7), 313s-322s (July 1956).

139. D. G. Howden, "Mass Transfer of Metal Vapour and Anode Temperatures in Arc Melting" - Dept. of Energy, Mines and Resources, Mines Branch, Physical Metallurgy Division, Internal Report PM-M-67-1 (Feb. 1967).

140. D. G. Howden, "Behaviour of Hydrogen in Stationary Arc-Melted Pools" - Dept. of Energy, Mines and Resources, Mines Branch, Physical Metallurgy Division, Internal Report PM-R-67-6 (Mar. 1967).

141. J. T. Berry and R. C. Allan, "A Study of Cracking in Low-Alloy Steel Welded Joints" - Welding J. 39(3), 105s-116s (Mar. 1960).

142. "Report of the Royal Commission Into the Failure of King's Bridge" - Government Printer, Melbourne, Victoria, Australia (1963).

143. W. P. Campbell, "Examination of Failed Section from a Bailey Bridge Panel" - Dept. of Energy, Mines and Resources, Mines Branch, Investigation Report IR 63-42 (Apr. 1963).

144. W. P. Campbell, "Examination of Failed End Piece from a Bailey Bridge Panel" - Dept. of Energy, Mines and Resources, Mines Branch Investigation Report IR 64-34 (Apr. 1964).

145. Phase Report of the Supervising Committee for Pipeline Research Project NG-10, "The Effects of Welding Procedures on Base-Metal Cracking Adjacent to Girth Welds and Welded Connections in Natural Gas Pipe Lines" - American Gas Association, New York (Oct. 1955).

146. C.S.A. Standard Z183, "Oil Pipe Line Transportation Systems" - Canadian Standards Association, Ottawa (June 1967).

147. V. S. Turkin and M. P. Anuckin, "Carrying Capacity of Steel Pipes and Calculation of Long-Distance Pipeline's Strength" - V.M.I.I.S.T., Moscow, U.S.S.R. (1962). (Submitted at 1962 Symposium on Pipelines organized by International Institute of Welding, Oslo, Norway June 1962).

148. B. J. Bradstreet, "Arc Welding Low Alloy Steels" - British Welding Research Association, Cambridge, England, 20 pages (Aug. 1956).

149. B. J. Bradstreet, "Methods to Establish Procedures for Welding Low Alloy Steels" - Eng. J. 46(11), 37-41 (Nov. 1963).

150. W. P. Campbell and K. Winterton, "Tentative Recommendations for the Avoidance of Underbead Cracking When Welding Steel Conforming to C.S.A. Standard G.40.12 General Purpose Structural Steel" - 8(B-4), 2-11 (Dec. 1965).

151. M. S. Titleman, "Fabrication of Welded Bridges" - Eng. J. 48(2), 19-24 (Feb. 1965).

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