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No. 779

WELDABILITY OF HIGH-TENSILE STEELS FROM EXPERIENCE IN AIRPLANE CONSTRUCTION, WITH SPECIAL REFERENCE TO WELDING CRACK SUSCEPTIBILITY

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WELDABILITY OF HIGH-TENSILE STEELS FROM EXPERIENCE IN AIRPLANE CONSTRUCTION, WITH SPECIAL REFERENCE TO WELDING CRACK SUSCEPTIBILITY*

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SUMMARY

Following a survey of the development and present state of weldable materials suitable for airplane construction, the writer proceeds to the less known difficulties encountered with the use of high-tensile steels - that is, their forms of occurrence, their causes, their prevention, and methods of testing.

The concept of welding crack tendency is explained and illustrated with practical examples. All pertinent causes are enumerated, and experimental measures are given through which the secondary effects can be removed and the principal causes analyzed:

1. Welding stresses;

2. Material defects.

The variations in length and stresses incident to welding a small bar as free weld, with restrained elongation and restrained elongation and contraction, are explored in three fundamental experiments. The so-called "clamp-weld test" is developed and compared with the "surface-flame test" and the "T-joint test." It is found that, other than the known indirect welding deflections on certain points of the weld, there is yet another kind of welding effect unknown in its cause, which we call "indirect" weld deflection.

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*"Schweissbarkeit von Stählen höherer Festigkeit nach den Erfahrungen des Flugzeugbaues, mit besonderer Berücksichtigung der Schweissrissigkeit." Luftfahrtforschung, October 1, 1934, pp. 93-103.

The effect of the material itself is explored in metallographic and chemical analyses of steels of varying welding-crack tendencies. The susceptible steels reveal peculiarities in both respects. Excessive C and (P+S) content appear to be the main causes of weld cracking, with impurities playing the more prominent role. The systematic examination of one special steel further revealed the feasibility of yet other factors influencing this susceptibility.

As second welding difficulty, frequently encountered on high-grade steels, the weld-hardness is explained, along with the causes which lie in the composition of the material in conjunction with the heat treatment incurred during welding.

Lastly, based upon these observations and experiments, the writer suggests certain test methods with which the weld-hardness may be ascertained and successfully removed. These are:

1. Determination of hardness distribution next to the seam;

2. Macro-etching of welds;

3. Bending test of welding lugs.

I. DEVELOPMENT AND PRESENT STATE OF WELDABLE STEEL

The use of gas welding in airplane construction, begun during the war and in the post-war period, was limited to soft - almost carbon-free iron - that is, deep-drawn sheet and soft-steel tubing. The plasticity of this metal, together with its comparatively low tensile strength, proffered the least difficulty for the manufacturer and the user and made it, in fact, the ideal material for experimentation on welding. Moreover, the melting heat affects the strength characteristics and structure of very pure iron very little, according to the metallography of welds (reference 4).

Until about ten years after the war, soft iron was almost exclusively used as welding material in airplane construction, although its welding strength (i.e., the minimum strength of the materials governing the calculation) did not exceed 34 to 38 kg/mm² (48,360 to 54,050 lb./sq.in.).

From that time on, we can trace a persistent attempt for materials of higher tensile strength, with a view to lighter and more economical structures. The next logical step was to raise the welding strength through higher carbon content, the natural alloying element of steel. Since, however, the traditional ideas and experiences - for the previously cited reasons - seemed to justify more or less grave misgivings against any higher C content, this avenue of attack was first subjected to exhaustive experimentation.

As concerns the effect of carbon content on the welding strength of steel, figure 1 is very illustrative. It shows the results of tensile tests of welds on carbon steel strip of varying C content, and represents the data of a total of 116 tensile tests made in 1928 with butt welds on five steel strips of varying C content (1-millimeter gage). For the rest, the sheets were quite similar and uniform and corresponded in compositions to the refined steel according to DIN 1661, but of greater purity. Aside from the scatter boundaries of the welding strength, figure 1 also shows the position of maximum frequency.

The attained welding strength thus increases from 32 to 38 kg/mm^2 (45,515 to 54,050 lb./sq.in.) with 0.07 percent C to around 50 to 70 kg/mm^2 (71,118 to 99,565 lb./sq.in.) with about 0.25 percent C, where the lower limit of the scatter zone then gradually begins to drop because the scatter zone expands in increased measure; whereas the location of maximum frequency (or concentration) rises continuously slower with increasing C content.

Therefore, a C content in excess of 0.25 to 0.3 percent serves practically no useful purpose as far as strength is concerned, if for no other reason than that the welds are narrow - i.e., about 2 cm (0.787 in.) wide, in which no appreciable welding stresses can occur. The experiments further proved that higher carbonization made certain zones of the weld hard, and others brittle; and even at that time (reference 4) it was recognized that the weld had a tendency to crack because the comparatively brittle steel was no longer able to equalize the stresses set up on solidifying, especially when the seams were long. It was during this period that A. Rechtlich made his investigations, according to which steel tubing of 0.34 percent C was still suitable for welding purposes in airplane design, while the use of higher C content was discouraged.

Since about 1928, however, sheet of as high as 0.27 percent C and tubing of as high as 0.3 percent C - and perhaps, even higher - have been welded to fittings and lattices without arousing much objection. Thus, it was possible to raise the theoretical welding strength to 50 kg/mm² (71,118 lb./sq.in.), or about 20 percent. Subsequently, the persistent attempts at weight saving compelled the use of alloyed steels, the procurement of which encountered considerable difficulty for some time.

The first materials taken over by the airplane manufacturer from the automobile industry were the Ni-Cr steels, to be used for parts without welding. The first attempts at welding them had proved unsatisfactory.

The casehardened Ni or Cr-Ni steels would have been more suitable, but they did not establish themselves, chiefly as a result of the commercial scarcity of supply and demand in form of drawn, seamless tubing and thin strip.

During the jump of the foreign steel manufacturers over Germany, as a result of abnormal war conditions, the United States developed the well-known chrome-molybdenum steel 4130, which has been successfully welded perhaps since the end of the war. Since 1930 such steels have also been used in German airplanes, resulting in a welding strength of 60 kg/mm² (85,340 lb./sq.in.).

Since that time the German airplane designer has gained a world of experience through experimental and theoretical research, and it is very opportune to pause and draw the practical applications therefrom; and in particular, to so perfect the weld-test methods that safety from the point of view of welding is commensurate with that of the other branches of airplane design. The hitherto conventional check-weld methods, generally restricted to the external appraisal of the welding operation and the finished weld, aside from the traditional tension, bending and folding tests, are no longer comprehensive enough for the weldable material entering airplane construction.

The aim in the following is to establish the criterions for adequate and reliable weldability of steels of high strength in the light of modern knowledge and experience in airplane construction. This raises the following questions:

a) What are the common difficulties and dangers encountered in welding high-strength steels?

b) What causes them?

c) What test methods are really adequate for appraising the weldability of steels used in airplane design and related branches of engineering, and how should these test methods be interpreted?

We summarily exclude the difficulties which are readily amenable to the conventional inspection methods, such as poor flux, unclean surfaces, insufficient strength, etc.

Much more dangerous, however, are the defects which defy routine inspection until discovered by the user or when the defect has actually caused failure. Such dangers lurk in the tendency of the weld to crack and in the weld-hardness.

II. WELDING CRACK TENDENCY

By this is meant the property of the material which tends to crack near the welded seam - usually in the joint between the bead and the welding work, at times extending even a few millimeters into the sheet or tubing; at other times opening wide, or else forming very minute hair cracks. They vary in length from a few millimeters to several centimeters. As a rule, they follow a slightly zigzag course, in the manner of a grain boundary failure; at times they form bracnhes such as quite often observed on fatigue fractures.

The cracks start, as readily seen during welding, between white and red heat; that is, between 800 and 1,000° C. temperature. Figure 2 shows some typical examples, while figure 3 is a photograph of two welding cracks on a steel tubing.

The striking fact is, that such cracks can occur and still defy outside detection until the exposure of the bead by back-and-forth bending in the weld reveals them on a ferric-oxide film and its annealing colors.

a) Causes

These are:

1. Stresses due to heat changes and correlated deformations;

2. Defects in the part to be welded;

3. Defects in rod material, gas, and oxygen;

4. Faulty welding operation:

   a) Torch adjustment, tip size, ratio of mixture;

   b) Holding of torch;

   c) Welding speed;

   d) Welding direction and order of rows;

   e) Type of tacking.

1. Experimental Procedure

The procedure was as follows:

1) All materials revealing a doubtful or suspicious tendency to weld cracking in the preparation and material testing at the Focke-Wulf airplane shops, and of which there was a sufficient supply available (as sheets or tubes), were carefully put aside and marked, in order to insure an adequate supply of testing material.

2) The actual welding was carried out by one of the oldest and most reliable welders under constant supervision of competent metallurgists. Torch adjustment, tacking, and order and speed of welding were prescribed very minutely.

3) The degree of purity of welding rod, gas, etc., was checked continuously, and with one and the same sheet of known degree of cracking tendency, the effect of these factors was observed, kept constant or, if necessary, removed.

From among the series of tests made in this respect,

we select here one made regarding the effect of the welding wire (fig. 3): A suitable weld was made with an unsound (i.e., crack-susceptible) steel pipe A, and a sound steel pipe B (the difference in the pipes having been revealed in practical welding operation on this very joint), and specifically three times, each with three different kinds of welding wires, or 18 welds altogether. Pipe A revealed 6 cracks in all, which - although unlike - divided over the three welding wires, while none of the 9 welds on pipe B disclosed a crack. This proved that the weld metal A itself was responsible for the cracks and not the welding wire.

The degree of purity of the acetylene gas, the gas-oxygen mixture ratio, and the size of the flame in their effects were observed in similar manner. It was found that a flame too high with respect to the sheet thickness actually promotes the cracking susceptibility, whereas the other factors left no noticeable effect. The welding speed throughout the experiments was kept within the usual limits of sheet thickness and about $1\frac{1}{2}$ times heavier welding wire and correct flame adjustment. The welds being short, as in the first experiments, the direction and order of weld rows are of no significance.

In this manner it was possible to observe the two chief factors: extent of the welding stresses or deflections, and the degree to which the material properties are the cause of weld cracking.

From the physical point of view, the query could be more adequately posed as follows: To what degree is the elongation due to heat changes on a crack at the precise instant, greater than on a corresponding place which did not crack? And how much less is the ultimate elongation in the crack than that in a corresponding non-torn place? These measurements are, however, difficult to effect, in view of the complex conditions and high temperatures, so that the more empirical way with practical welding tests was preferable.

In this connection, be it noted, the detection of the causes and the suitability of test methods for weld-cracking susceptibility had to be effected concurrently rather than separately.

2. Welding Stresses

The formation of weld cracking may be visualized as being primarily due either to the formation of an oxide film between the grain boundaries ("burned" steel, reference 1), through which the cohesion is markedly reduced and the steel becomes easily separated at this point, or else that the separation of the highly heated steel initiates cracking and engenders the oxidation of the cracked areas.

In the first case, cracks or oxide films could form even when there are no stresses; but, according to numerous observations in actual welding practice, this phenomenon does not occur except where it can be accompanied by stresses. The cracks were never observed on free-weld seams of less than 2 centimeters length, so that the simple weld-tension test (free weld of small width) gives absolutely no clue to the cracking tendency of a metal. From further experience accumulated in airplane design, it is found that the cracks run, almost without exception, parallel with the seam.

Fundamental experiments.- The three basic experiments described hereinafter vouchsafe much information regarding the formation and effect of welding stresses:

Butt-welded rods of small enough section (10 × 1 mm = 0.3937 × 0.03937 in.), so as to produce practically linear deflection or stress conditions at right angles to the seam, were measured for length changes during welding and solidifying with the fixture (fig. 4) under the following conditions:

1) In the absence of all external forces acting on the bar;

2) With restrained elongations but free lengthwise contractions of the bar which might occur as a result of heat changes;

3) With the bar tips - i.e., the regions not affected by the welding heat - rigidly clamped during welding and cooling, thus preventing the two tips from moving toward or away from each other.

The results of these measurements are qualitatively expressed in figure 5. In the first case (curve A) we

note a rapid growth of the bar (0.55 to 0.7 mm = 0.02165 to 0.0276 in.) at the start of welding. Toward the end of the welding operation, the motion slows down and on solidifying, the stretch disappears again completely, conformable to the superposition of the length changes in the different heat zones, and this return is very exact, provided no external loads are applied at the ends of the bar. Contrariwise, even the tiny force produced by the dial gage pin resting on the bar reveals, after cooling, a reduction in length relative to that observed at the beginning of the welding operation. For the case in point, it already amounts to approximately 0.1 mm, the load of the pin being 32 g.

The second experiment (fig. 5, curve B), while revealing no elongation, discloses a contraction during solidifying almost exactly like the elongation of the first test. Owing to restraint in elongation, there is a complete plastic flattening in the fluid zone which then readily crushes under very low stresses after the first test. The shrinkage on solidifying is then exactly as that for the perfectly "free weld"; or, in other words, restrained elongation has shortened the bar on solidifying by an amount equivalent to this restraint.

The described tests were made on different bars of deep-drawing sheet St VII 23, St C 16.61, St C 25.61, and chrome-molybdenum steel strip. It was established that the diversity in total heat elongations, rather than being due to the type of material, was markedly influenced by the momentary extent of the heated zones, which in turn is intimately connected with the gage of the sheet. Another striking fact is the absence of difference in weld elongation on easy-cracking or sound material.

In the third experiment on welded and cooled bars with very rigid clamping, the dial gage, upon release of the clamps, revealed only a fraction of the shrinkage observed in the first tests (fig. 5, curve C); that is, a contraction in exact proportion to the yield limit of the annealed material. Being rigidly clamped, the bar had to yield the entire shrinkage as stress elongation which, depending on the location of the yield point of the heated zone, remains in part elastic, whereas the other part changes to plastic stretching of the soft annealed bar zone, provided the bar is without weld cracking. It was soon found that one steel was susceptible to it, while the other was not.

Surface flame test, clamp welding.- It was on the order of this last experiment that the so-called "clamp welding" was developed in the first reports treating welding-crack tendency, and tried out by the Focke-Wulf company. But before proceeding to details, the following should be noted: Even though there had been no systematic and thorough exploration of the weld-cracking tendency, as far as is known, there nevertheless existed a kind of test procedure for it, and which was occasionally used in airplane construction. This refers to the so-called "surface-flame" test or, as it is also called, the Fokker test (reference 2).

A piece of the particular sheet or tubing is brought to fusion with the welding torch by applying, without welding wire and without filler rod, a flame over small sections of the tube or plate surface from the edge toward the inside or vice versa, although the first is the more rigorous test. A good weldable material should stand this test, at least the less rigorous one from within toward the outside, without cracking into or next to the seam of the burn.

However, with the exception of fairly soft iron, the surface-flame test is totally unsuitable for ascertaining the weldability of a metal. Aside from that, the test cannot be applied to tube or strip of small dimensions.

The clamp-weld test was carried out as follows: Two butt-joint specimens are clamped at the usual distance (about sheet thickness) in a solid frame so as to flatten on welding by an amount equal to the thermal expansion, and to yield the same amount of shrinkage on solidifying as stress elongation, if no crack is to develop. After clamping the strips are exactly straightened in one direction and welded together in the orthodox manner from one end to the other without tacking (forward or left-hand welding). The specimen is released after cooling, examined under magnifying glass, and the bead exposed by bending back and forth in the seam (fig. 6, bottom). Then the percent proportion of the oxidized break readily discerned on the annealing colors, is ascertained as "weld-cracking tendency." The bead side with the majority of cracks is decisive for this.

From among the different clamping devices experimented with, the fixture shown in figure 6 is the best, both from

the viewpoint of reliability and economy. The two specimens (a) are pressed, by means of clamping device (b) and two nuts (c), against the two faces of a heavy U-shape stirrup (d); that is, pressed 1 mm deep into a cavity of the clamps.

Another important factor is the matter of size of the test specimens. For sheet and tubing, the thickness is predetermined and, the dimensions being small, the stresses may be accurately enough considered as a uniplanar problem. Thicker sheet or massive pieces must be worked to thin wall thickness. The described tests were made, in general, with 1-millimeter wall thickness.

As to the effect of specimen length, the above-described basic experiments for determining the linear welding deformations afford some information. According to them, the test is most rigorous when the clamped length includes the total heated distance, because then the crushing and the ensuing elongations are, evidently, highest. A still greater clamping length would again moderate the test, because the elastic elongation corresponding to the length, would increase; that is, the forced, permanent deformation would become less - whence a clamping length of 70 mm (2.76 in.) between the cupping points. On this place the temperature for the particular wall thickness does not exceed 100° C. at the moment of welding (reference 6).

The effect of specimen width - not being so readily ascertainable - was established on three 1-millimeter thick specimens of varying width (fig. 7). Leaving aside isolate irregularities for the moment, the following main points were established:

1) The percent proportion of oxidized cross-sectional area grows with the specimen width, reaching an average maximum at 50 to 60 mm (1.97 to 2.36 in.);

2) For 45 to 55 mm (1.77 to 2.17 in.) specimen width, the scatter zones are smallest and the measurements most conclusive.

The causes for this are, briefly, as follows:

It is clear that heat crushing and elongation, as observed perpendicular to the welded seam, occurs similarly

within the seam itself in its longitudinal direction when welding together two flat plates of adequate length and width. This had already happened on the wide bars in the last-described test, with the result that the ensuing multiaxial stress conditions weakened the deformation power of the metal and thus favored cracking. Thus, a width of 50 mm (1.97 in.) appeared most promising and was then preserved for the standard specimen.

The clamping stirrup was so designed that at the instant of incipient weld cracking, the stress amounted to approximately 3 kg/mm² (4,267 lb./sq.in.) only. In practical welding operation, the rigidity of clamping is very diversified; but as the requisite degree of clamping is governed by the purpose of the clamp weld itself, the appraisal of the employed test method may be briefly summarized as follows:

The clamp weld has proved very useful in the running material test for

1) numerically ascertaining the tendency of the material to weld cracking and through it, to

2) completely forestalling such cracking in welding operations.

To 1) it is added that: discounting a larger number of pieces from the same charge, the average of three samples is intended as the criterion for weld-cracking tendency, because the individual results scatter the same as in the tensile tests of wood or castings. Even the individual steels were frequently observed with varying scatter zones.

To 2): the permissible boundary of this cracking tendency must be decided for each case as it arises, according as stresses may or may not occur on the welded parts. On the basis of available comparative tests and operating experience, these fairly low percentages do not appear serious, being for small welds very minute points. The Focke-Wulf company has, up to now, made 1,962 clamp welds on pure and alloyed steel sheet and tubing, the majority by far showing very good results (welding-crack tendency 0 percent). A small fraction showed a very low percentage, while about 10 percent of the specimens, having a cracking tendency of from 10 to 30 percent, were scrapped. The Albatros Co. at Berlin, had exactly the same experience.

T-joint test (No. 4, fig. 2), representing a wing fitting.- An angle section (50 X 50 X 100 mm = 1.97 X 1.97 X 3.94 in.) and a piece (50 X 100 mm) of the same metal were tacked in the middle and at the end. After cooling and straightening, the pieces were welded together over the tacking, starting from the free end. The experiments made in Bremen and independently in the Albatros factory on identical steels, revealed the surprising fact that the T joints had a consistently much higher degree of welding-crack tendency than the clamp joints with the identical material. Some representative figures have been collected in table I.

TABLE I. Clamp Versus T Joint

	Sample No.	1 mm sheet Percent of susceptibility to crack Individual	Average	Sample No.	2 mm sheet Percent of susceptibility to crack Individual	Average
Clamp joint	1 2 3	5 12 10	9	1 2 3	0 4 0	2
T joint	1 2 3	48 40 30	38	1 2 3	38 20 50	36

Direct and indirect weld deformations.- Since the marked discrepancy between these figures could not be satisfactorily attributed to a more rigid clamping of the T joint than of the clamp weld, it was necessary to find some other explanation, and in subsequent weld deflections it was found that those of the T joint are actually additive to those for the clamp joint.

During the process of making the T joint the sheets develop heat zones (isotherms) approximately parallel with the seam of from 100 to 300° C., rising toward the center as high as the melting temperature of the steel. Naturally, these unlike temperatures are followed by different length changing tendencies parallel to the weld seam. The type and amount of these deflections are governed (apart from the form of the piece, tacking, etc.) by the mean expansion coefficients and strength factors pertaining to the particular temperatures. Both factors are given in

the particular temperatures. Both factors are given in figure 8 versus temperature. They reveal the very significant fact that, from about 600° on, the strength of the steel becomes very low, which means that the points of lower temperature (up to about 600°) prevail over the higher heated points with respect to heat deformations. And in this decisive range of low temperature the heat elongation rises almost linearly.

Owing to the approximately parallel zones of equal heat relative to the seam, the sheets in the T joint buckle swallowtail-like outward and stretch the highly heated, less solid zones in and on the weld seam in vertical direction to the seam.

Assuming a heat zone of 200° near the outer edge, and 30 mm (1.18 in.) away from it toward the seam, an isotherm of 600°, the crack which could occur on an unalloyed steel with 0.22 percent C alone due to bending between the ends of the two free pieces of 50 mm (1.97 in.) length in the weld seam, is computed at 0.59 mm (0.023 in.). This elongation is, in the present case, coincident with the cowling; that is, the contraction of the weld seam and the two types of welding stresses or deformations are superimposed in the sense of a stretch crosswise to the seam. This explains the intensified cracking tendency of the T joint.

Other methods of tacking, such as omitting one tack, or changing the direction of welding, affect the results in the anticipated manner.

These facts contributed to our knowledge on welding stresses and their causes as seen from the following. The tensile deformations occurring on a weld in any direction may be due to two causes:

1. The clamping and heat effects prevalent in elongation direction, i.e.,

   a) prevention of heat elongation which induces the crushing of the intensely heated zone of low strength;

   b) prevention of corresponding heat contraction, causing stretching first in the highly heated, then in the solidifying zones.

2. Additional motion of the clamp ends of the particular section, caused by concurrent or locally unlike heating in the higher strength zone (below about 600°). Here we differentiate between

a) additional temporary crushing of the highly heated metal in the particular direction during process 1.a), in which case it is followed by a greater stretch than quoted under 1.b);

b) additive stretching in the particular direction during the process described under 1.b).

The part of the deformations based on the processes described under 1. may be called direct, the other indirect, welding deformation. The indirect deformations or stresses have not been recognized heretofore, as far as the writer has been able to ascertain. That a welded joint should be made from the center toward the edge rather than from the edge toward the center, was a purely experimental experience, which cannot be adequately explained except through the knowledge of the indirect welding stresses.

For example, the indirect welding stress described under 2.b) in the T joint, is additive to the direct stresses. It could be in the surface-flame test also which, of course, largely depends upon the sheet widths available on either side of the "burn." If these are large enough the effect is prevented; if not large enough, it does not occur at all. Incident to the flame test proceeding from the edge toward the center, there is yet another effect of the kind described under 2.b): The flame passing over the sheet before reaching the "burn" heats these places so that the temperatures decrease with increasing distance from the weld, through which this is forced asunder by wedgelike acting elongations. This effect is approximately concurrent with the cooling of the "burn" and increases the cracking hazard.

The effect cited under 2.a) may, for example, occur in the T joint at the precise instant when the tack in the center becomes fluid and the start of the weld has already become solidified. Then, of course, the sheets buckle temporarily in the center.

In this manner the significance of welding stresses or deformations as cause of weld cracking is largely ex-

plained. They are a requisite premise for the occurrence of cracks; they may occur in an entirely different degree and consequently act in totally different measure as cause of cracking. On the other hand, they do not constitute a sufficient condition for mandatory existence of welding cracks, since the individual kinds of material may be able to compensate for any existing welding deformations in an entirely different degree.

Another fact worthy of mention is that the described investigations and deductions give some very pertinent facts regarding the effect of tacking, order and direction, and welding; and the forward or backward welding on the ensuing stresses.

The arguments also apply to nonferrous metals whose weldability often is frustrated by this selfsame cracking tendency (reference 8).

3. Material Defects

The second problem pertained to the extent and to certain material properties in their causative relationship to weld cracking.

Metallographic investigation.- These tests, made on sound and unsound welds of all kinds, reveal the cracks as following mostly along the grain boundaries, branching out at times, and frequently hiding inclusions - probably, ferric oxides. Sometimes decarbonization is noticed on the crack edges; at other times, not. Materials very susceptible to cracking mostly manifest on the nonwelded micrograph, strikingly marked liquation zones and comparatively large slag inclusions. The micrographs of welds of crack-conducive (unsound) carbon steels quite often reveal in the large perlite grains of the "overheat" zone peculiar ferrite spots of compact form without inclusions in its center instead of the Widmannstätten ferrite needles.

These impurities evidently acted as inoculation points for the unusual ferrite segregation. The "overheat" zone of a very susceptible steel tube closely interspaced with such ferrite spots, is shown in figure 9, where the inclusions within the ferrite spots can be partly recognized. Figure 9a illustrates the normal "overheat" structure of a good weldable carbon steel. This occurrence together with

the known fact that sulphur causes red-shortness, raised the conjecture that these inclusions might be ferric sulphide because, since the eutectic Fe-FeS becomes fluid at 985°, it might be that at the moment of cracking, the connection of the steel is not only interrupted in places, but that probably as a result of an increased volume of liquid eutectic, the remaining section itself becomes subject to initial internal stresses.

So, by tempering such macro-etchings, it was attempted to render the constituents lying within the ferrite spots visible as ferric sulphide on the blue color tone (reference 1) which, however, was not altogether successful because of its smallness and similarity with manganese sulphide, despite very great enlargement.

Chemical analyses which, expressed in a few words, comprised a number of steels (sheet and tube) of varying weld-cracking tendencies, collected from actual practice and experiments. This analysis revealed four distinct groups in order of size of cracking tendency.

Silicon and manganese content do not seem to cause cracking. Even from the other constituents, one alone is not the cause, although certain compositions of C and (P+S) should not be exceeded. The established relationship of the weld-cracking tendency of those with C and (P+S) content, is shown in figure 10.

Owing to the slight difference in P and S, the individual figures of the analysis did not reveal which was the objectionable element - phosphor or sulphur - although the analysis affirmed the conjectured sulphur effect of the metallographic investigation.

During the investigations it was found that in special steels, yet another factor may cause such cracking tendency.

The marked susceptibility of such a steel, explored very thoroughly, was, with moderate carbon content and satisfactory purity, not quite reconcilable with the other results from analysis. The micrograph showed the "overheat" structure of pure carbon steel with normal Widmannstätten ferrite needles. But the striking fact was the low silicon content which, perhaps, in some way is conducive to weld cracking. On the other hand, it is conceivable that this susceptibility is caused by some peculiarity in manufacturing process or to the existence of some other admixture.

In the more recent tests on several kinds of steels, it was noted that the frequency of slag inclusions in the micrograph runs more parallel with this susceptibility than the P and S contents, which is indicative of yet other causes.

Lastly, we point in table II to some observations made on several alloy-steel tubes and sheets, which contained, for the rest about 0.25 percent Si, 0.5 percent Mn, 1 percent Cr, and 0.25 percent Mo.

TABLE II. Crack Tendency and C Content of Chrome-Molybdenum Steels

Sheet or tube No.		1	2	3	4	5
Crack tendency	Individual	0,0,0	0,0,4	0,7,0	2,9,2	10,2
	Average	0	1	2	4	6
C content in percent		0.20	0.27	0.28	0.31	0.33
S content		trace	-	-	-	trace

The salient fact is that the crack tendency arrived at without knowledge of the analyses rises fairly uniformly with the carbon content; besides, that this cracking tendency as a result of the very fine degree of purity, is still low even with comparatively high carbon content.

In view of all these observations, it is positively certain that the tendency to cracking in welds, is a property locked up in the different steels in the most varying degrees. Although its cause in special steels has not been completely cleared up, one important result may be put down, namely, that the purity of (P+S) = 0.07 percent quoted in DIN 1661; and which heretofore has been largely considered as adequate for welding steel (reference 2), is far from sufficient for the problem in hand. The higher the welding strength - that is, the carbon content (see fig. 1) - of an unalloyed steel is to be, the lower the (P+S) content must be kept.

Judging from individual preliminary experiments, the hot- or cold-work condition appears to have no effect on the degree of crack tendency. Clamp welds of Cr-Mo steel refined to 120 kg/mm² (170,680 lb./sq.in.) revealed no in-

crease over the soft annealed state with about 60 kg/mm² (85,340 lb./sq.in.) tensile strength. Even a small cold draw of C and Cr-Mo steel tubes failed to intensify the hazard of welding cracks.

b. Avoidance and Testing of the Welding Crack Tendency

Cognizant of the danger of weld-cracking tendency it is, obviously, the concern of everybody to forestall its occurrence on all vital welds. Aside from the burner adjustment, another chief cause noted was the coincidence of unfavorable material properties (lack of purity) with direct and, in totally unfavorable cases, indirect welding deformations due to clamping effect, faulty tacking and heat distribution.

In a well organized welding shop, the rules governing correct burner size, neutral flame adjustment, and slow cooling rate must be carefully and consistently enforced by the foreman and the metallurgist. The previously cited examples of T-joint and surface-flame test reveal that the indirect welding stresses, once they are known, can be easily avoided or at least minimized by correct tack welding, direction of welding, flame adjustment, etc., as, for example, by resorting to backward or right-hand welding. But the direct welding stresses are not always possible to avoid. Steel tubes in airplane construction, for example, are welded into lattices, where it is impossible to prevent the last welded piece from being subject to a regular clamp-weld condition. When large sheets are welded through a longitudinal seam to a plate, the first part of the welded seam after cooling, acts as clamp for the subsequent seam portions.

For successful labor in material manufacture, to render materials as little as possible conducive to weld cracking, an adequate test method is the requisite premise. In this endeavor, some concerns even use the so-called "cross-weld" test, consisting of two 50 X 200 mm (1.9685 X 7.874 in.) strips, placed crosswise in the center and welded together on the four edges by four fillet-welds of 50 mm length each. This is to avoid cracking near the seams.

But this test is accompanied by similar direct and indirect deformations, as observed in the flame test. Aside from that, the shrinkage of the fillet-weld causes the strips to bend away from the flame of the strip, which favors the formation of cracks even more. However, this ef-

fect is very distinct according to the accidentally more or less smooth fit of the two strips.

The one test method giving clear conditions is the clamp-weld, where the clamping effect is obtained by suitable design of the specimen itself, or through a clamping or welding jig. Such a specimen jig is imperative for testing tube or strip. To make such a test method universal, it must be known in its details.

According to experience gained from the current clamp-weld tests and its results in service, it may be said that for airplane steel tubing, the upper limit of the transition zone (shaded portion of fig 10) must not be exceeded. For strip, the lower limit should be adhered to.

III. WELD-HARDNESS

This is a second error easily encountered in high-strength steel, which has not been observed enough hitherto in the practice of weld testing. By this weld-hardness is meant that the material in a zone modified by the welding heat becomes so hard and brittle as to induce difficulties from the point of view of finishing or of strength.

A piece of metal should, even after welding, be heat-treatable and shapable. If the high-tensile steel is to be heat-treated subsequent to welding, it is impossible to do so in many cases, as with airplane bodies and tail units, for example, at least with the means available at present. Owing to warping or inaccurate scale, both of which are mostly inevitable, the welded parts must, as a rule, be straightened, and then this very zone of maximum hardness and brittleness - in most cases, right next to the welded seam - suffers the most. Aside from that, the notch effect caused by the joint between bead and "overheat" zone increases the danger of cracking when straightening. Still, drilling and thread-cutting next to the welded seam should not be rendered abnormally difficult by air-hardening.

Moreover, with increasing heat next to the welded seam, the vibration strength of the weld is weakened severely starting from a certain point, as proved from fatigue tests on welded steel tubes (reference 4). Consequently, the weld-hardness constitutes a hazard well worth

the attention of manufacturers and users, especially of weldable alloy steels.

a. Causes

The cause of this weld-hardness is primarily found in the composition of the steel. The attempts at higher material strength lead, as stated, to higher carbonization and alloying of the weldable steels. Even the need for high treatability should be mentioned in this respect. And here in the sometimes one-sided concern about a high enough strength, the permissible limit of the admixtures is easily exceeded, according to experience in welding practice. Other than the special alloying elements, carbon and manganese are almost always heavy contributors to the hardness effect. Added manganese lowers the transformation points and the critical cooling rate, at which the secondary crystallization becomes suppressed. Owing to the high heat, the solution of the carbides is very complete and the γ grain grows comparatively great. These two facts, together with the higher rate of cooling of the thin wall thicknesses, are very detrimental for the formation of secondary crystallization and, if accompanied by large admixtures, may easily lead to martensite spots in what is largely a sorbite-like structure or even completely martensitic "overheat" zones. It should be the concern of the welding section to prevent higher cooling rate caused by abnormal conditions, such as draft, too low outside temperature, or placing the parts on cold, heat-conducting spots, such as iron or stone surfaces.

Weld-hardness and cracking tendency, be it noted, are not correlated; i.e., weld-hard steel need not be responsive to cracking and vice versa.

b. Testing and Avoidance of Weld-Hardness

In the search for an adequate method for checking well-hardness, the well-known folding test comes first to mind. Instead of the homogeneous bar, a bar is fabricated with a cross-weld in the center, and bending and folding is then applied in the zone of this cross seam.

For testing an electrode on thick sheet and correspondingly wide welding seam, this is a practical, technological test of the rod material and the welded seam; and perhaps of the weld itself, so far as within this ambit of application air-hardening steels are generally excluded. But for

conditions involved in light construction, this type of test is unsuitable for the following reasons. For the thin wall thicknesses in question here the weld seam shall be thicker than the wall thickness itself, and this has a twofold result:

First, because the structure thus obtained scarcely permits a uniform bending of the kind described, with the result that the data vary very considerably, according to the experimental contingencies; second, since for welding high-strength steel, a little milder rod material, especially as to C content can be utilized because of the greater section - a fact which is freely taken advantage of both from the point of view of metallurgy described in the beginning, and of economy. (The softer iron flows more readily.) Therefore, the danger point in these cases in question lies, in general, in the welding material rather than in the welding wire.

For similar reasons, Rechtlich (reference 2) resorted to the folding test with two metal strips, welded together in the middle throughout their whole length, so that the welding bead itself and each zone by itself could be bent simultaneously. But even this type of test has not proved satisfactory in every way. The stress and deformation conditions are rather vague and dependent on the perhaps accidentally irregular welding bead with its many sectional variations. This makes the results of his tests very inconsistent and reveals little of that which is actually wanted.

Recommended test methods for determining whether and to what extent a steel is to be appraised as weld-hard, are:

1. Determination of hardness distribution next to a welded seam.

2. Macro-etching of weld.

3. Bending test of welding lugs or straps in the hardest zone, defined conformably to (1).

The first-named test is as simple as it is enlightening. At a distance of at least 3 mm (0.118 in.), starting directly at the seam the hardness and strength are ball-tested up to the unaffected material, and the data plotted. This relation with the maximum and minimum strength figures

affords the material expert a very clear insight into the properties of steel. (See fig. 11 and table III.) Using Rockwell hardness F (ball diameter, 1/16 inch, loading 10 + 50 kilograms (22.05 + 110.23 pounds)), the test may be made on high-tensile steels up to 1 millimeter wall thickness.

Macro-etching also affords a good indicator of the weld-hardness of steel. The proportion of martensite prevalent in a welding zone is a sure index of corresponding weld-hardness.

Lastly, the following bending test has proved quite adequate: 20 X 30 mm (0.787 X 1.181 in.) lugs or straps from the particular sheet or straightened tube are fillet-welded in a row on a piece of scrapped metal tube, then clamped in a vise and bent back and forth with a pair of flat pliers, the tips of the jaws being located at twice the sheet thickness away from the bead. The bending alternates toward the sides of the fillet seam, emplaced at one side. (See fig. 12.) Bending can be very exactly stopped at the first crack, as at that instant the bending stress, after a distinctly felt maximum, comes suddenly to a stop.

With the described set-up, the result for 6 lugs - the mean angle of bend - is readily obtained, projected on a protractor and read. This bending test has, compared to those mentioned above, the added advantage of lucidity and uniformity of result as well as closer accord with conditions encountered in practice. According to experience gained from practice, as well as untold tests, the strength in the "overheat" zone should never exceed 90 to 100 kg/mm^2 (128,012 to 142,235 lb./sq.in.) if difficulties are to be safely avoided. Then the macro-etching is altogether without martensite, and the possibility of bending the welding straps or lugs should be at least 90 degrees in both directions. In the running material test, it is advisable first to resort to macro-etching or the Brinnell test and then, if some doubt remains, to bending tests.

In testing as in fabrication, it is self-evident that normal cooling conditions must be maintained.

Figure 11 and table III give the properties of three steels. Steel No. 3, owing to excessive weld-hardness and correlated vitiating properties, should not be used in aircraft construction.

Translation by J. Vanier,
National Advisory Committee for Aeronautics.

TABLE III. WELD-HARDNESS VERSUS PROPERTIES OF STEELS (FIG. 11)

No.	Brand	Wall thickness mm	Maximum hardness next to seam H(2.5/187, 5/30)	Structure of "overheat" zone	Weld resistance σ_B kg/mm²	Weld resistance σ_W kg/mm²	Mean bending angle of lugs
1	C steel C = 0.33 percent	2	170	Coarse perlite grain with Widmannstatt needles in ferrite net	50	20	90°
2	Cr-Mo steel	1	250	Sorbitic ferrite-perlite	60	22	90°
3	Cr-Mo steel	1	350	Coarse-grained martensite	64	17	40°

mm x 0.03937 = in.

kg/mm² x 1422.35 = lb./sq.in.

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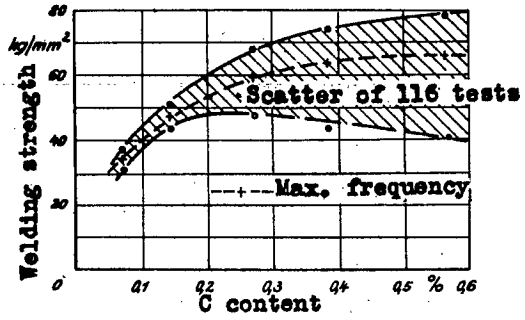


Figure 1.- Welding resistance of steels of varying C content.

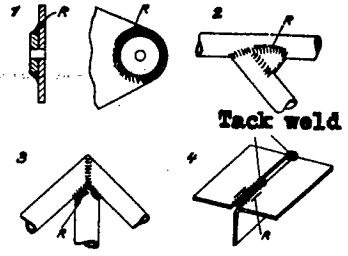
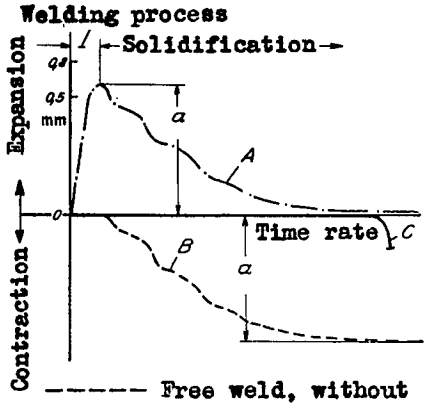


Figure 2.- Illustrations of welds with welding cracks R



------ Free weld, without external forces.
——·—— Expansion restrained, shrinkage free.
——— Clamp weld, shrinkage measured on solidifying.

Figure 5.- Elongation - shrinkage stresses on a small specimen (qualitative only).

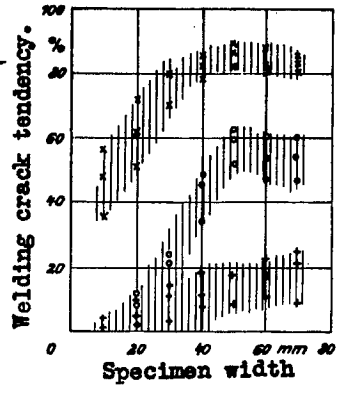


Figure 7.- Effect of specimen width in the clamp weld test, on three sheets of varying degrees of weld cracking tendencies.

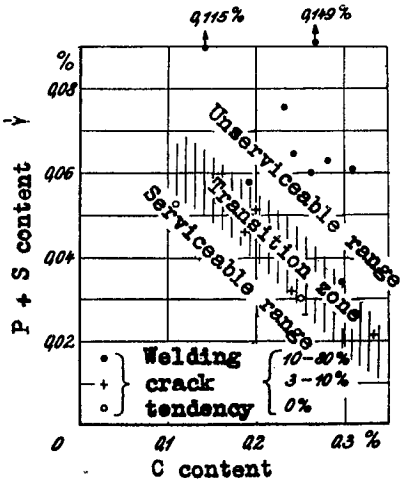
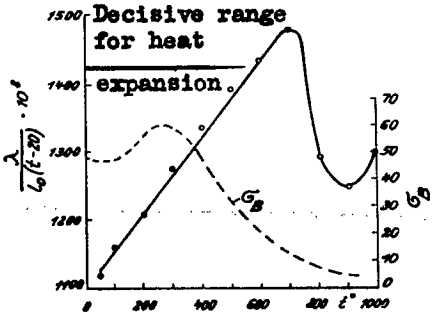


Figure 10.- Effect of C and (P+S) content on the welding crack tendency of non-alloyed steel.



------ Strength versus temperature
——— Mean elongation coefficient at various temperatures referred to 20° C (Oberhoffer)

Figure 8.- Steel with 0.22% C content.

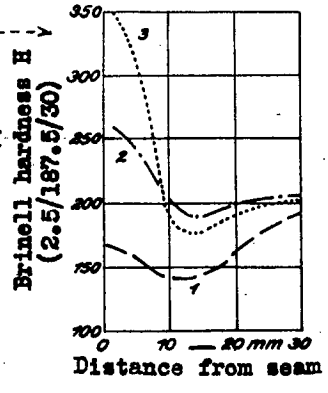


Figure 11.- Effect of Brinell hardness H in welds of different steels.

Figure 3.- Welding cracks on steel tube.

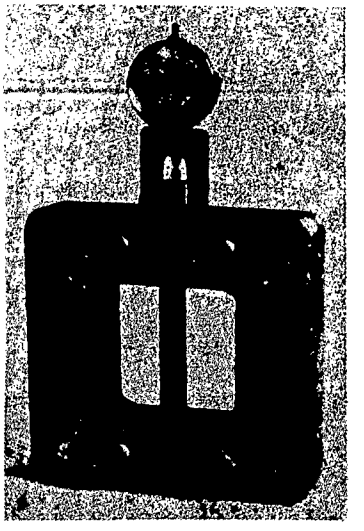
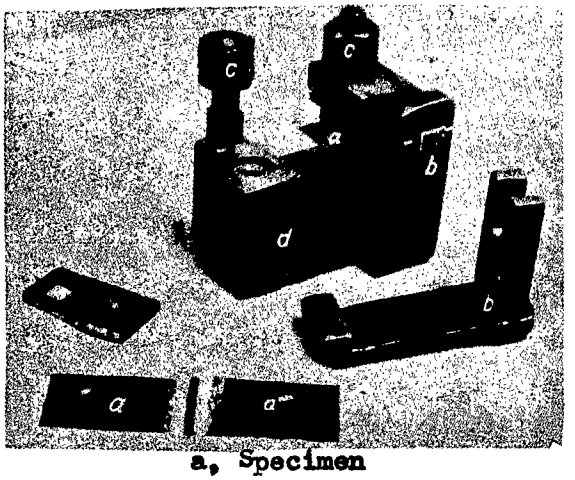


Figure 4.- Fixture for determining linear weld deformation perpendicular to seam. The specimen is clamped at the bottom, leaving a clearance of about 0.1 mm on top.



a, Specimen
b, Clamp
c, Nuts
d, Clamp stirrup

Figure 6.- Fixture for clamp weld.

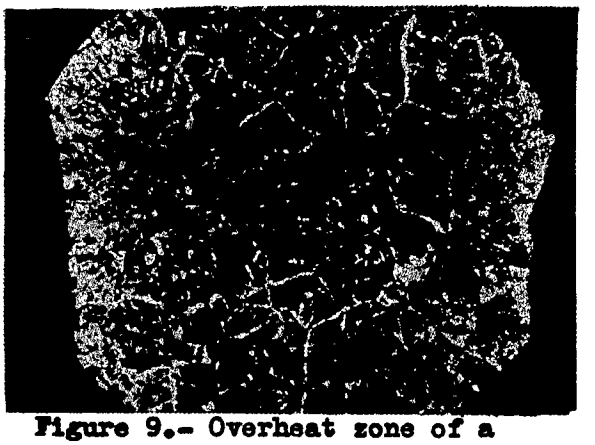


Figure 9.- Overheat zone of a very susceptible carbon steel with its peculiar ferrite spots.

Figure 9a.- Overheat zone of a non-conducive carbon steel; ferrite as net work and Widmannstatten needles.

Figure 12.- Bending test.

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