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Controlling the Effects of Shrinkage.

Zur Beherrschung der Schrumpfwirkungen.

La lutte contre les effets de retrait.

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The practice prevailing in structural workshops when carrying out riveted constructions used to be that of merely subjecting the rivet material to a heat treatment; however, when welding methods began to be applied, a fusion process was introduced into the workshops concerned. Quite apart from the usual difficulties which beset every metallurgical process, conditions in this case are particularly difficult because small quantities of liquid material at very high temperatures have to be melted to form part of a much larger mass of cold material.

1) Demands made on the Material being used.

This local melting down of one material so that it may form part of other material requires conditions entailing very marked differences of temperature and an equal lack of uniformity with regard to conditions governing expansion and cooling. This lack of uniformity in changes of temperature is the cause of those phenomena which in welding technique go by the name of shrinkage or contraction effects.

The speed at which cooling proceeds depends on a number of different factors, namely: the welding method employed, e. g. — electric arc welding, resistance welding, Arcatom-welding or gas fusion welding. In the case of electric arc welding, the speed depends on the electrode used, which may be plain or covered; it also depends on the working conditions prevailing and the methods applied. These differences are sometimes very great and where circumstances are very unfavourable they may induce effects which resemble those set up after quenching. Very abrupt changes in cooling speed play an important part when the materials being welded are such as show signs of hardening or develop brittleness if cooling is proceeding too rapidly.

These effects are sometimes observed when steel having a high content of carbon is used and also with steel alloyed with elements having an excess percentage of hardening properties, elements such as manganese or chromium, and this is the case more especially when cooling proceeds fairly quickly.

The weld metal while cooling undergoes certain changes. The austenite which is present after solidification undergoes various changes of texture, passing from martensite, troostite, and sorbite, until finally it is found in the form of stable perlite = or ferrite-cementite. When cooling proceeds slowly, the changes referred to above take place in the regions of high temperature in which no stresses are set up as a result of the changes of volume consequent upon the physical changes.

Where additions of carbon or alloy exceed a certain amount, these phenomena of physical transformation may induce corresponding stresses resulting from the changes, because when cooling is rapid the changes of form settle in the lower zones of temperature in which more marked resistance of form to changes of volume is observed and in which, furthermore, the thermal tensions reach very high figures. Another possibility is that the change from austenite ⟶ perlite, desirable when using ordinary structural steels, does not occur when certain alloys are added, nor when cooling is effected very suddenly, but that in certain circumstances the structure of the metal in the weld-zones will finally be of an intermediate composition; where circumstances are most unfavourable, a hard and brittle martensite will be produced.

Experience has taught us that a mild unalloyed steel with a low carbon content, such as is used in steel structural engineering, does not set up any of these undesirable phenomena. When using steel containing little alloy, this problem may possibly become more serious. In order to avoid deleterious effects, the bending test with metal in the tempered state should be carried out; to this end the steel at 900° C. is quenched in oil at indoor temperature after which it should be possible to bend the steel round a mandril having twice the thickness of the metal plate. This last operation is also carried out at indoor temperature.

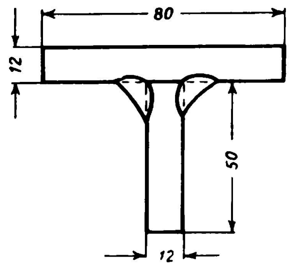
Steels which are to be welded may have only a moderate content of impure ferrous matter, such as sulphur and phosphorus. Sulphur is known to cause "hot brittle" fracture; if the sulphur content is too high there will be some danger of cracks occurring before the metal cools. Phosphorus sometimes causes "cold short" fracture; steel containing too much phosphorus tends to give the structure a coarse grain which results finally in small cracks appearing in the neighbourhood of the welded joint.

Sufficient margin for the change of form of the weld metal when cooling does not necessarily guarantee immunity against cracking. It is highly probable that most cracks start while the temperature is still high. (Section 6.)

When the sections or plates are of increasing thickness, that is, according as the volume and rigidity of the parts to be welded are greater, the risks of cracking also increase. This is probably very largely due to the higher conduction of heat and thus the problem discussed above in connection with steels having high carbon contents may also be significant in the case of structural steels of low carbon content.

It is necessary, therefore, to carry out suitable experiments with a view to eliminating types of weld metals which induce cracks when used for welding basic material of the kind in question. The German State Railways have recently introduced a test for resistance to fracture which is used when approving welding rods and electrodes. (Fig. 1.) I believe I am right in saying that many firms who wish to improve their welding rods carry out similar investigations under even severer conditions, namely, by using heavier metal plates.

Mechanical processes, such as machining, for instance, frequently used to combat shrinkage effects in welded parts (Section 7 b), often require, just as other mechanical processes do, that the weld be machineable, not only in a hot, but also in a cold state, so that welding rods and welding conditions which induce an excess absorption of oxygen and nitrogen may be eliminated.



Fig, 1.

Test to investigate the predisposition of electrodes to cracking.

The fact that shrinkage effects have to be taken into account makes it necessary to eliminate welding rods having excessive exothermal properties, that is, those which melt too easily when subjected to unusually intense heat. The effects of heat can be easily gauged by observing the extent of the tempering zones next to the welded joint. The use of welding rods which are known to extend the zones of heat effect unduly should be definitely prohibited in steel construction.

2) Processes of Expansion and Contraction.

The visible effects of heating, e. g. deformation which becomes apparent in the form of shortening of the metal-bending and buckling, will be dealt with only inasmuch as they help to elucidate the problem of shrinkage stresses and cracks caused by shrinkage or contraction. Control of deformation has been far more extensively developed by industrial enterprise than has investigation of the problem of how to reduce tension and cracking, undoubtedly because deformation is much more striking than are the latter phenomena. Quite frequently the measures taken to prevent undesirable changes of form lead to increased stress and to risks of fracture. For this reason it is sometimes advisable to aim at some adjustment in order to solve the problem of deformation and tension occurrence satisfactorily.

a) Transverse Contraction.

When molten metal in a liquid state is allowed to move unrestrictedly, it has the property of contracting uniformly in all directions. In practice unrestricted contraction in a transverse direction occurs only in the case of butt welds and then only in welds which have been executed fairly rapidly. Unhampered contraction is never possible in a longitudinal direction.

When plates which are to be welded are placed in position for welding without being rigidly fixed, transverse contraction takes place as a consequence of the welding groove becoming narrower under the effect of the heating of the parts to be welded, and also because the filler material which has been used contracts. The first of these two factors is by far the more important. The amount of heat used also influences transverse contraction, and that amount depends on the size of the section of the weld and on the specific heat consumption required to melt the welding rod.

H. Koch[1] and *R. Malisius*[2] have carried out detailed investigations on what takes place when transverse contraction is proceeding in butt welds, and we owe the following data to their work.

Contraction takes place where welding is continuous because the melted weld metal is poured gradually into the joint and thus, instead of spreading evenly over the whole length, it moves forward lineally. Tacking, if properly carried out, will reduce contraction considerably, and where such contraction does occur, its course will be along parallel lines. The welding of a joint in sections may have similar effects if correctly executed, for instance, when using the "step-back" welding procedure; as a rule it will be preferable to reduce contraction by weld-tacking as much as possible.

Contraction increases with increased thickness of the plate, because the central width of the weld is increased. (Fig. 2.) Transverse contraction can be

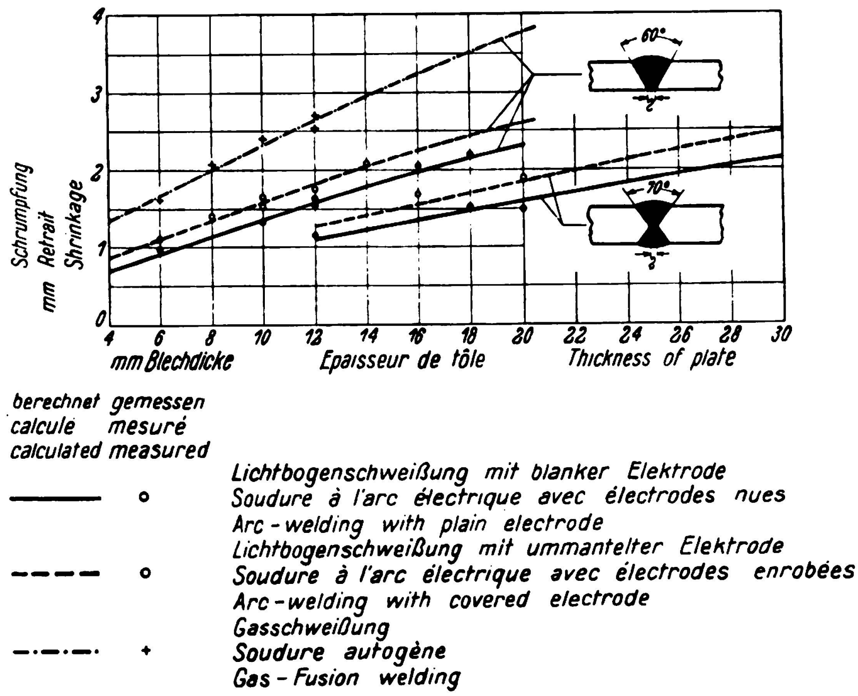


Fig. 2.

Transverse shrinkage of welds of well-tacked joints.

attenuated by considably reducing the cross section of the joint so far as this can be done without prejudice to the weld. (Fig. 3.)

Multi-layer welding, usually applied for heavier plates, sets up an angular contraction alongside the parallel one and this may lead to bending of the metal. The entire contraction in this kind of joint consists of parallel shrinkage and angular shrinkage. (Fig. 4.)

Angular contraction, and also the entire contraction, increases very consid-

[1] *H. Koch:* Contraction and Contraction Stresses in Connection with Electric Arc Welding. Treatise T. H. Hannover, 1935.

[2] *R. Malisius:* Contraction of Butt-welded Joints. Series: Information Concerning the Theory and Practice of Electric Welding (Publ. Vieweg) H. 2 and Electric Welding 7 (1936) Pp. 1 to 9.

erably with increase of the thickness of the plate. The number of passes of weld metal is also of great importance. In Fig. 5 the conditions requisite for V-joints with plates of 12 and 18 mm thickness respectively are seen. In order to prevent an excess of angular contraction and of the entire contraction, it is advisable to keep the layers thin and to use thick welding rods or electrodes in preference to thinner ones. If the number of passes is too limited, the structure

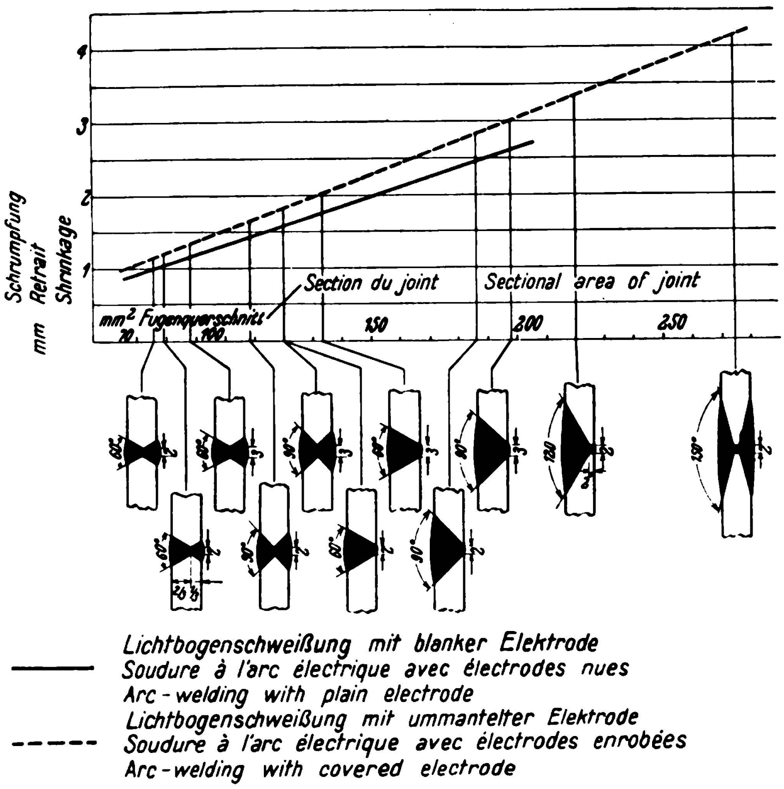


Fig. 3.

Shrinkage of butt welded joints of different shapes (plate thickness 12 mm).

of the metal will be adversely affected and there will be some danger of cracks being formed.

Conditions can be much improved by using symmetrical or quasi-symmetrical joint cross sections, in particular if the weld layers in the upper and lower joints are welded alternately[3].

Transverse contraction and angular contraction play an important part with fillet welds. Both these contractions can be limited, just as in the case of butt welds, by using welding rods which do not require an undue consumption of heat, and provided the weld cross sections are kept as small as is compatible with the production of sound welds. Risks of cracking do, however, occur if the fillet welds or first passes of weld metal are too thin. (Section 6.)

Transverse contraction is less marked in fillet welds[4] than in butt welds

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[3] *E. Höhn:* Welded Joints in Boiler and Container Construction, Pp. 56/59. Published by Springer, 1935.

[4] *Lottmann:* Welding applied to Shipbuilding. German Publ. Strauss Vetter & Co., Berlin, and Electric Welding *1* (1930) Pp. 133/4.

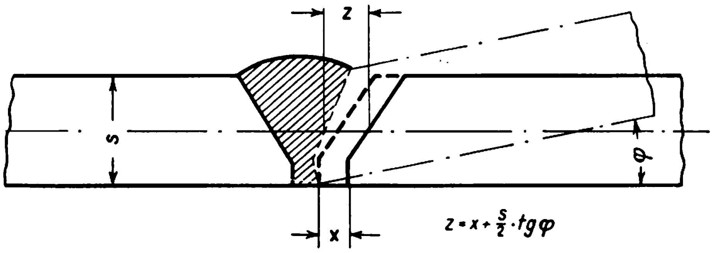


Fig. 4.

x = Parallel transverse shrinkage. φ = Angular shrinkage. z = Total transverse shrinkage.
Component parts of transverse shrinkage.

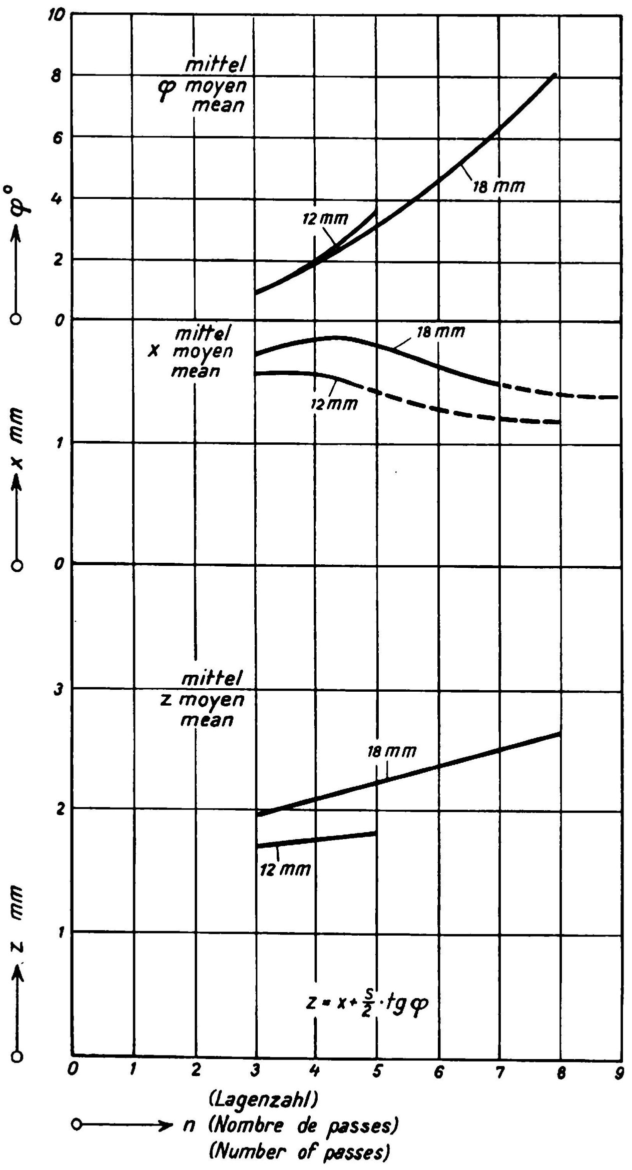


Fig. 5.

Shrinkage in relation to the number of passes for plates of constant thickness (12 and 18 mm) acc. to H, Koch

Constant: l = length of weld 180 mm; b = total width 240 mm; V-shaped weld; v = width of joint 3 mm.

Welding process: arc-welding with alternating current and covered electrodes 4 and 5 mm dia.

Normal amperage; clamped at both ends.

(Fig. 6), as the zone affected by the melting process reacts on a certain part of the thickness of the metal only. When dealing with cross sections of welds which maintain their uniformity, we shall find that the transverse contraction does not depend on the thickness of the metal as in the case of butt welds; it is more likely that there will be less contraction with heavier plates. Contraction depends very largely on the welding road and its diameter, and also on the working methods used. Every enterprise has its own particular manufacturing practices so that tests should preferably be made on the type of joint usually adopted.

b) Longitudinal Contraction.

When depositing the intensely hot molten weld metal into the joint, the neighbouring zones of the latter which are also at a high temperature will expand, but this change of form in the direction of the welded joint can be effected only in connection with the colder parts at the side. The comparatively abrupt drop in temperature which always accompanies welding and the ever

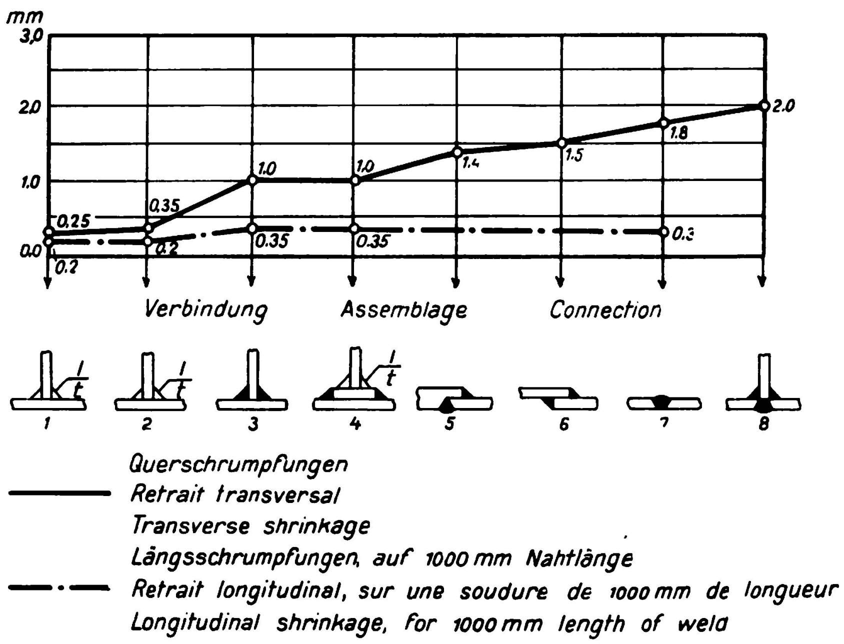


Fig. 6.

Transverse and longitudinal shrinkage of welded connections acc. to Lottmann.

increasing heat coefficient of expansion which is not stable at higher temperatures, induce plastic "upsetting" in the very hot zones and this is the real cause of the longitudinal contraction and contraction stresses which are set up.

When using ordinary carbon steels the ductile limit starts in the neighbourhood of 600 to 700^0 C., after which it rises comparatively quickly as the temperature drops (Fig. 7). The zone of 600^0 C. is surrounded by zones which offer little resistance to deformation and by others with increasing resistance, and this signifies that the maximum of plastic "upsetting" is to be found at this point.

When carrying out electric arc welding, in particular when using polished electrodes, the zone having a temperature above 600^0 C. is a very narrow one, thus the maximum "upsetting" takes place in close proximity to the weld seam. Where the zones subjected to heat are wider, the points of maximum "upsetting" are generally outside the welding zone (Fig. 8). The transition from

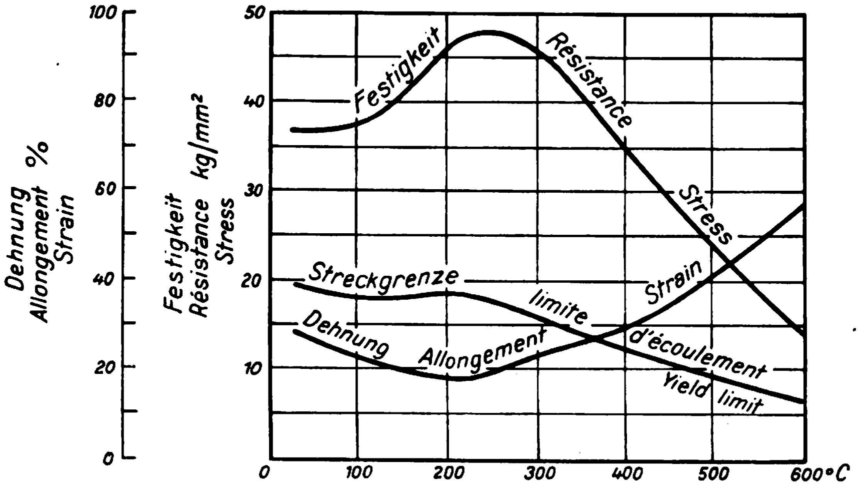


Fig. 7.

Strength properties of non-alloyed steel acc. to G. Urbanczyk.
C = 0,14%; Mn = 0,51%; P = 0,016%; S = 0,032%.

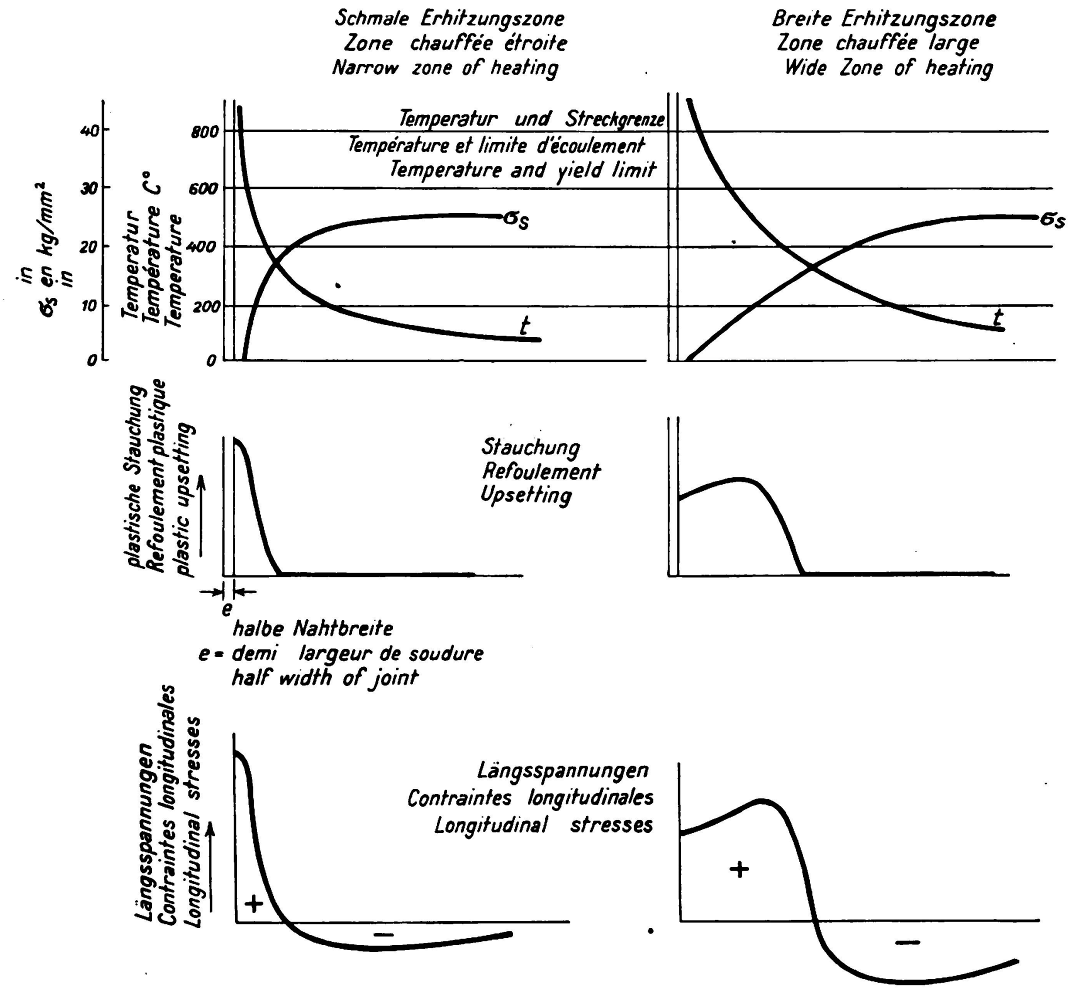


Fig. 8.

Temperature, upsetting and stress conditions for narrow and wide zones of heating.

basic material having low resistance to deformation to that of higher resistance is less abrupt in proportion as the changes in temperature of the larger zones of heat are more gradual. The maximum "upsetting" is therefore lower.

Longitudinal contraction is practically only a fraction of transverse contraction (Fig. 6). Formerly the conclusion frequently drawn was that the remaining shrinkage stresses in the direction of the weld were low, and thus the phenomena of longitudinal contraction stresses were not considered to be very important. This shrinkage stress problem can only be dealt with rationally if, contrary to the above opinion, it is tackled by starting with the longitudinal contraction and its effects.

3) Shrinkage Stresses when for part loosely held in position.

Those parts which have been only slightly heated and those which have suffered elastic deformation only during the process of welding will try, when cooling, to regain their original length, while the welding zones which have been shortened by "upsetting", will try to attain a length which is shorter than their original one. They are prevented from doing this, however, by the connection that exists between them and those parts subjected to elastic deformation only. The result is the setting up of a weld stress in the direction of the weld, with high tensile stress in the weld itself and in those zones of higher temperature and also of corresponding compressive stresses (stresses of reaction) having similar tendencies due to equilibrium in the cold or moderately hot parts of the material.

Where the zones of heat are narrow a high tensile stress is induced which covers a very narrow zone of the welded joint. Where the zones of heating are wider the tensile stresses will be less intense and the highest coefficient will be found beyond the joint, while the zone under tension will be proportionately greater. The compressive stresses of reaction are low in the narrow zones of heating, while where the zones are wider, the compressive stresses and warping will be considerably increased (Fig. 8).

Transverse stresses are set up at the same time as the longitudinal ones. This has been observed in the first place in connection with butt welds; the position as far as fillet welds are concerned is more complicated (Section 5 d). The assumption here is that the transverse contraction is not hampered by clamping of the material or by internal tension (Section 5 a).

If the temperature of the joint is raised, a slight, even if unnoticeable, outward curving of the edges will take place so that the distance at the ends of the joint will be larger than at the centre. While cooling proceeds the bending back action will be more marked under the influence of the longitudinal contraction of the shortened zone of welding. The weld metal which has been run into the joint and which is cooling will be pressed against the ends of the weld joint under these influences, while in the central parts they will be drawn apart (Fig. 9). (The term "non-rigid" in connection with welding or welded parts is thus shown to be antithetical and can be interpreted solely as characterizing external conditions.)

The longitudinal and transverse stresses which are set up have to comply with the conditions imposed by equilibrium (Fig. 10). The state of tension has

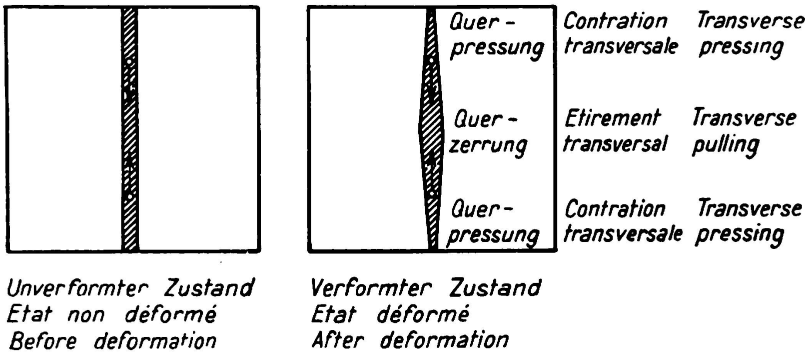
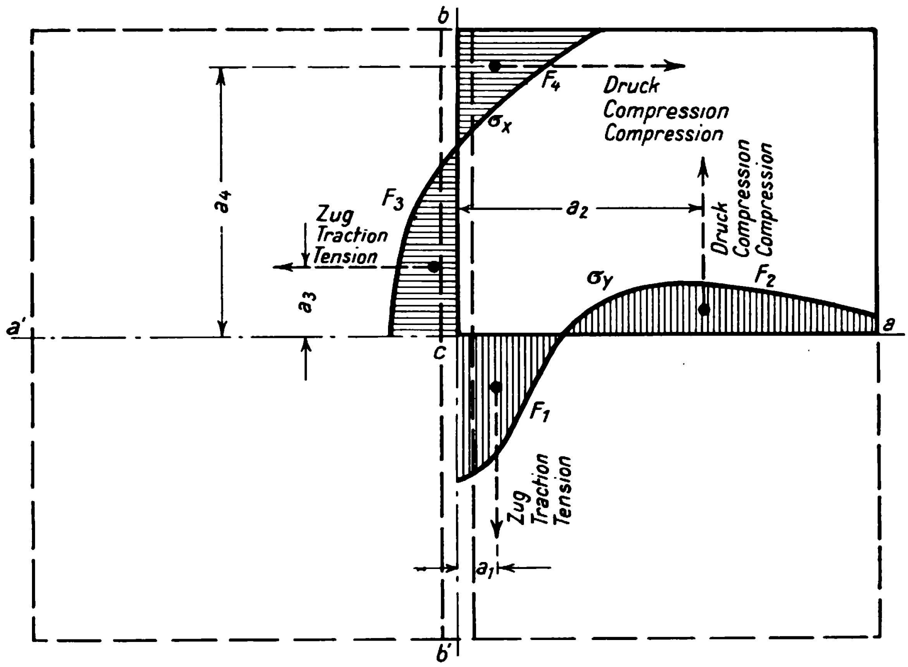


Fig. 9.

Longitudinal shrinkage causing transverse stresses for free welding.



$F_1 = F_2; F_3 = F_4$

$F_1\ a_1 - F_2\ a_2 = F_3 \cdot a_3 - F_4\ a_4$

Fig. 10.

Relation between longitudinal and transverse stresses based on internal equilibrium.

been described by the author as the "natural welding state of tension", because it corresponded to the peculiarity of fusion welding in which connections are made by means of narrow joints filled with weld metal.

In practice it will always be necessary to take certain stresses into account (Section 5). Welding showing no "transverse tension" is possible only when the weld metal is run simultaneously into the whole length and depth of the groove and when resistance welding is the system applied. Nevertheless it is a fact that when a large number of important butt welded joints are made, the influence of transverse contraction is so far lessened that the conditions of "non-rigid" welding constitute the decisive factor. Transverse stresses which are caused solely by longitudinal contraction in the absence of any transverse stress, are indeed so great that they must not pass unnoticed even in cases in which tension is set up on a large scale.

Experimental investigations have confirmed the arrangement of longitudinal and transverse stresses in butt welds as decribed above (Fig. 11, Plate 20, 3 and 15). Even with welds of greater length and thickness and welds consisting of

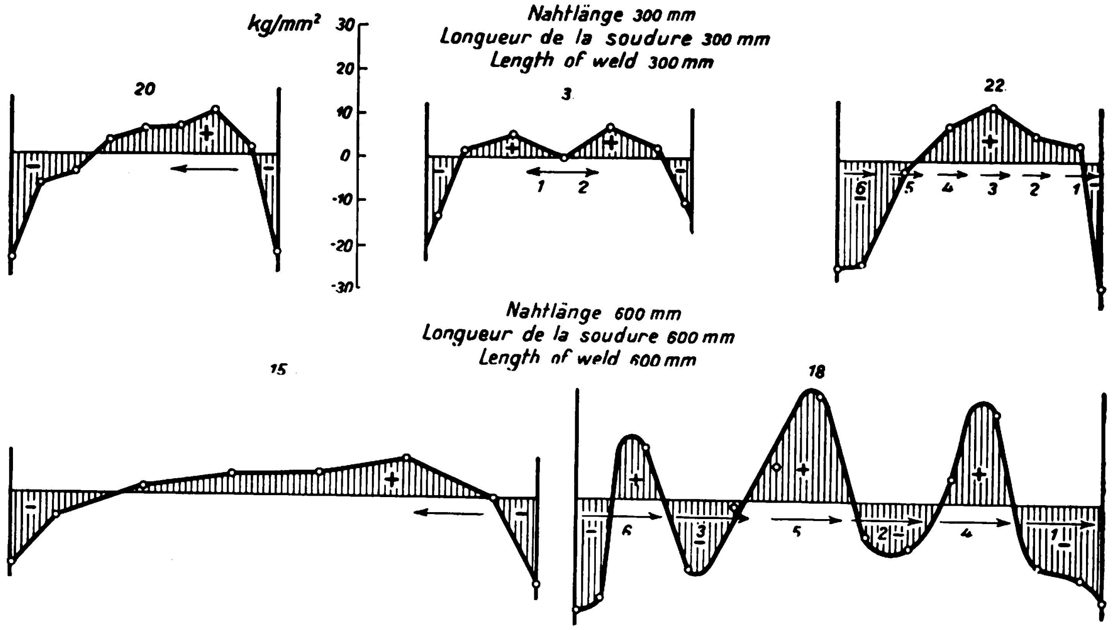


Fig. 11.

Material: St 37. Thickness of plate: 12 mm. Welding process: arc-welding. Welding wires: Böhler "Elite" cored electrodes. Number of layers: 3. Transverse stresses in welds for free welding and different forms of weld stepping.

several layers[5], something similar to this state of stress is observed, so that it is really of great practical importance. The most essential feature is the occurrence of intense compressive stresses at the extremities of the weld, and this offers a certain natural safety factor for the ends.

Experiments have proved that the effects resulting from the transverse stresses due solely to the longitudinal contraction and exerted on the resistance have no bad results provided these stresses alone have been set up.

[5] *G. Bierett:* Experimental Investigation into Shrinkage Stresses in Welded Butt Joints. Publication by Association of German Engineers, 78 (1934) Pp. 709/715.

G. Bierett and *G. Grüning:* Contraction Stresses in Autogenously Welded Members. Aut. Treatm. of Metals. 27 (1934) Pp. 259/266.

G. Grüning: Welding and Shrinkage Stresses. Steel Structural Engineering, 7 (1934), Pp. 110/112. For summaries of these three treatises v. Comm. of German Mat. Testing Inst. Special publication 25, Pp. 65/86.

F. Bollenrath: Autotension in Electric Arc and Gas Fusion Welding. Treatise. Aerodyn. Inst. Techn. College, Aix-la-Chapelle. 1934 H. 14. Pp. 27/54.

F. Bollenrath: Further Investigations on Self-Stresses in Ordinary Welded Joints. Archives of Mining Industry. 9 (1935/36), H. 4. Pp. 203/207.

4) Longitudinal shrinkage stresses.

Longitudinal shrinkage stresses are of particular importance in steel structural engineering for welds which run in the main direction of forces. The cross section of the welding zones constitutes as a rule only a small portion of the entire cross section. The term "welding zone" as used here refers not only to the cross section of the weld itself, but also to that part of it which is at a higher temperature and which has been clenched when in a heated plastic state. Apart from exceptional cases, the entire cross section vertical to the welded joint, as compared to the cross section of the weld-zone, will always be a very large one.

Intense tensile stresses occur in the welding zones, while the rest of the section is mainly under compressive stress. The conditions governing tension in the weld zones themselves are of importance for those parts which when in commission are exposed to tensile stress also, and the compressive stresses (stresses of reaction) set up by the process of welding are important for the other transverse parts which are subjected to compression.

The longitudinal weld stresses reach their maximum where the high temperature zones are narrow and when the weld metal, or the parent metal, is very strong. If the parent metal is of unsatisfactory quality, and particularly if the various parts of the job are massive, there is some risk of cracks forming across the welds. Parent metal or welding rods that give rise to defects of this kind should be eliminated before starting on the work.

The extension of longitudinal weld stresses can be reduced by extending the heating zones. Welding rods which set free large amounts of heat and welding methods or processes having similar effects are favourable from this point of view. This fact should be considered when dealing with members of a structure which are under tensile stress only. Meanwhile it must be remembered that when the heating zone is larger, the resultant power of contraction which influences greater width increases and simultaneously the opposing compressive stresses increase. Therefore when members are under compressive stress only, it is advisable to set up an intense tensile stress in the welded joint affecting a limited zone rather than less intense tensile stresses which, while extending over a larger zone, set up higher compressive stresses. All these effects should be taken into account when selecting the welding rod or electrode. In electric arc welding, this point of view should — for instance, in the case of compressive members — take precedence of other requirements such as deformation capacity. In girder construction it is necessary to avoid excessively narrow zones of heating, at any rate for the longitudinal welds in the tension flange; in the compression flange they should be limited as far as possible. This differentiation in selection is not at present customary in practice; however, full use of all existing possibilities would certainly contribute to improved conditions.

Very little definite evidence is forthcoming regarding the figures for compressive tensions of reaction which might be useful to designers from the point of view of risks of fracture, or to workshops when considering the effects of warping. *Doernen*[6] has laid down the compressive stresses of reaction for the webs of welded I-girders.

It can be deduced from this investigation that the designer should limit the weld cross section to a minimum. On the other hand, in these cases the workshops must limit as far as possible the cross section of the zones of the weld by appropriate measures and these measures should include the use of welding rods which do not set free excessive amounts of heat, and should carefully comply with the regulation cross sections for welds.

Fig. 12 shows the results of measurements of actual tension of welded rolled sections in which visible compressive stresses occur at the edges. Even if it appears in these cases as though the higher actual compressive stresses do not influence stability to any great degree — and the results of bending tests carried out on that type of structural member by the State Material Testing Laboratory at Berlin-Dahlem seem to confirm this — all possible means of the kind referred to above should be applied in order to obtain a really well designed structure.

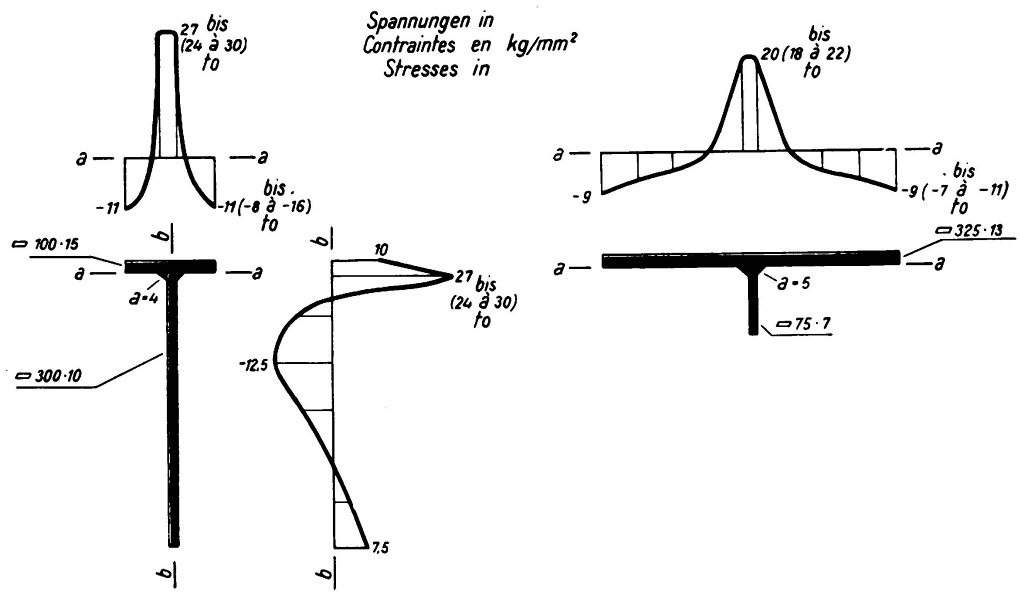


Fig. 12.

Welding stresses along the welds in sections welded with fillet welds.
Electric arc-welding.
Note: The figures in brackets are for extreme values as determined by numerous similar investigations.

5) Transverse Stresses.

a) *External and Internal Transverse Stresses.*

There may be some transversal obstruction to the process of expansion and contraction

a) due to external rigidity. Such external rigidity in this connection should be taken to mean the clamping or fixing of the parts to be welded

[6] *J. Doernen:* Contraction of Welded Steel Structures. Steel Structural Engineering *6* (1933), Pp. 22/24.

previous to carrying out the welding. Examples of this kind are: web welded joints connecting continuous flange plates or flange plates already welded and flange plates and web joints welded for the purpose of connecting massive structural members;

b) due to internal rigidity or tension. By internal rigidity of a welded joint is meant in the first place the tension existing in those parts which, while not rigidly fixed, are adjacent to the sections or layers of weld which have been terminated and which prevent the possibility of welding the joint along its whole length without setting up transverse stresses. These stresses are induced by the fact that it is not possible to carry out simultaneously the operations of melting, welding, heating and cooling the various sections of the joint and the various runs of weld metal; these operations have to be carried out in rotation.

c) The tensions which arise when fillet welds are made resemble the effects of clamping;

d) As special cases mention might be made of welding patches into the material or the welding of plates on to larger members by means of welds that cover a large portion of the structure. Even where the whole weld is executed in one single operation transverse stresses are set up in this class of work. Circumstances are therefore similar to those observed with external rigidity.

e) External and internal rigidity or tension are often induced simultaneously.

b) Connection between transverse stresses and a) thermal conditions and b) physical thermal properties of the material being used.

Thermal expansion of the heated parts adjacent to the zones of welding leads to "upsetting" of the welding zones in cases where tension exists in the region of higher temperatures. This thermal expansion is increased in proportion as the heating zones are larger. Thus the additional transverse shrinkage stresses depend mainly on the amount of weld metal deposited into the joint and on the specific heat consumption per unit of weld metal that has been melted. The transverse shrinkage stresses seen in Fig. 3 represent a standard by which to measure tension variations for various sizes of weld cross sections; however, the stresses there shown are merely the result of the narrowing of the joint due to the effects of heat and contraction of the melted material flowing into the joint while the differences are still greater in the heated zones owing to "upsetting". When welding, the process of contraction takes place first of all in the welded joint and runs contrary to the expansion of the welded parts owing to the effects of the heat which is escaping. When welding parts that are clamped, this expansion acts in a compressive way on the welding zones. The physical properties of the material being welded influence these processes very considerably; such physical properties are: coefficient of expansion, specific heat, heat conductivity and ductile limit and these are not determinate coefficients but factors which are affected by temperature and therefore elusive when it comes to calculating them. When gauging the effect of these factors, however, it is easy to note that with large supplies of heat conditions will be less favourable than with small ones; experiments and practical experience have confirmed this.

c) Measures for reducing tension effects.

One of the most important conditions underlying the reduction of external and internal stresses and necessary in order to obtain welds exempt from excessive transverse stresses, is that of keeping down the size of the weld cross sections and the elimination of welding rods which require undue specific heat consumption.

The most reliable way of reducing external stresses or anything that resembles it is by elastically shaping the parts adjacent to the joints and by appropriately dealing with each welded seam in turn. This complicated task will be considerably lightened if the edges of the joint are previously slightly bent out of the plane of the plate (where transversal joints are unsymmetrical the bend should be to the side of the widest part of the joint), and this practice should be still more strictly followed when welding plates requiring two parallel joints or when welding plates into or onto parts with joint along the whole circumference. An important example of this class of work is that of a web joint in a universal joint of a girder (Fig. 13). A slightly cylindrical intermediate piece, not too

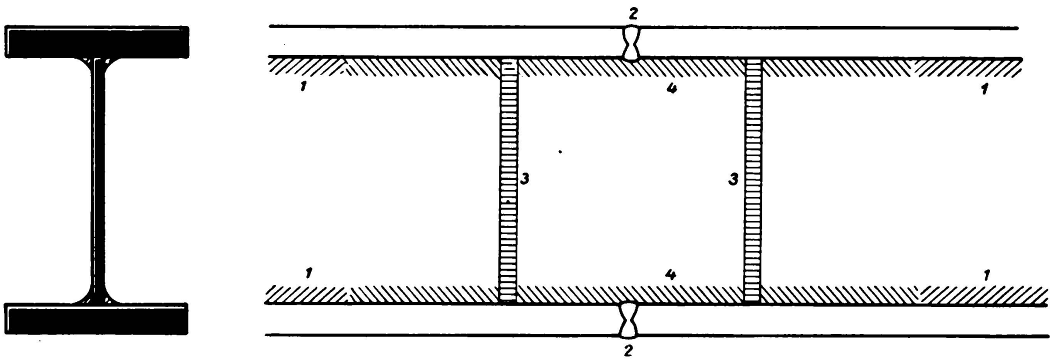


Fig. 13.

Appropriate welding procedure for girder joint.

short, should be used and elastic sections provided in the neighbouring web members by leaving the adjacent collar joints provisionally open; this will facilitate the execution of the web joint even if the joints of the small flange plates have been closed down as they ought to be. The prevention of the contraction of the flange plate resulting from resistance to friction can be eliminated by measures which promote the process of contraction, for instance, by adding coupling nuts, or some similar device.

Internal tension of a weld seam, which according to the explanation set forth in Section 5 is induced in the weld seam only as a result of the welding process, must therefore be prevented mainly by skilful execution of the weld. In this connection the sequence followed when welding, the speed of welding and the number of layers run into the joint, are of importance.

The transverse tension along the joint is a result of having to run the weld metal into the groove and to cool in two separate operations. This transverse tension is proportionately less according as the field of temperature between the end of the finished part of the weld and the beginning of the weld is more uniform. This means that high welding speed is useful because it reduces the transverse tension over the length of the welded seam. In practice this transverse tension can be very much reduced by application of heat while welding (Section 7 a), or, and this is the more common practice nowadays, by welding in stages. The best method here is that called step back welding in which welding proceeds, after starting at one of the weld-ends or from the centre, by advancing symmetrically in both directions (Fig. 14). This method is particularly

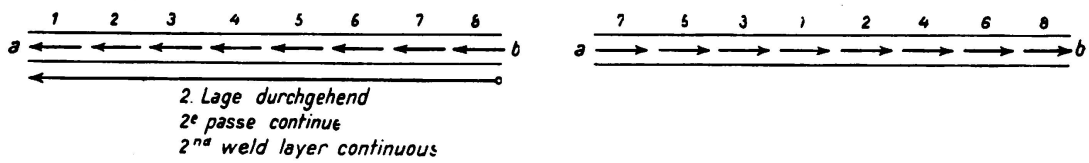


Fig. 14.

Step-back welding method.

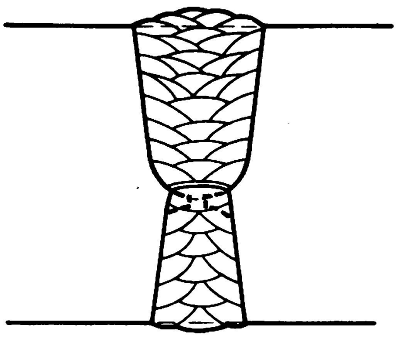
advantageous to the first run of weld metal, because in the first place the risks of cracking (Section 6) and the overlapping of the unfinished ends of the welded joint (the latter occurs frequently in continuous welding on account of the heat that precedes execution of the weld) are considerably reduced, while the subsequent layers are often welded continuously by alternating the main directions. The stages or steps vary in length from 10 to 40 cm according to the length of the weld and the thickness of the plate; when the welded joints are very long the "steps" are sometimes still longer than the figure mentioned; tacking should be correctly carried out and at intervals equal to the length of the "steps". The so-called "welding in steps" should not be used as it tends to set up intense transverse stresses (Fig. 11, Plate 18).

The application of continuous non-interrupted welding has found great favour in ship building, which necessitates the welding of very long seams. When welding plates on to other metal members its application is practically indispensable. This method is also very useful in girder construction for the production of fairly long web connections, in particular for the welding of the first run of weld metal in the joint and probably also for long continuous weld seams.

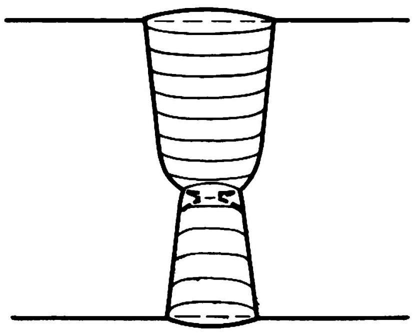
When dealing with short lengths up to 400 mm, continuous non-interrupted welding offers no advantage. When welding medium-length butt welds of 500 to 800 mm or more, such as are commonly used in steel structural engineering, this method may be useful for root-welding if any external tension is present. As a rule, however, these welds can be executed in one operation or in two sections, and this offers no difficulty. If the joint is made in two sections and there is no external tension present when welding from without towards the centre or from the centre outwards, it is probable that a high compressive tension will be induced at the ends of the weld. With external tension a weld made from the two ends towards the centre offers more certainty that the compressive stresses at the ends of the weld and the tensile stresses will be but very slight.

The tension above the top of the weld can be reduced by applying correct welding methods, by giving the joint the right shape and by making the right number of layers. It is obvious that one sided welds, built up by a large number of thin layers, are bound to result in very unequal distribution over the section of the weld and marked peak tension in the top layers.

Symmetrical or quasi-symmetrical weld sections — alternately welded as far as possible — are generally preferable[7]. No uniform practice exists in the various spheres of application of welding technique with regard to the number of layers, the arrangement of the welding bead in the cross section of the seams, or the diameter of the welding rod. Tank designers basing their practice in the matter of welding heavy plates[8] on experience covering many years, are adopting the use of heavier welding rods increasingly. Meanwhile the layer must be neither too thick — e. g. 3 to 4 mm — nor too thin. Welding proceeds in wide layers or runs passing from one side of the joint to the other. In steel structural engineering, on the other hand, heavier welding rods are not very commonly used, in fact, exceedingly thin welding rods as compared to the heavy plates being welded are often employed. Broad layers of weld metal are not produced, generally merely narrow welds (Fig. 15) and this is made in such a way that



Raupenanordnung
Disposition en chenille
Arrangement of passes



Lagenanordnung
Disposition en passes
Arrangement of weld layers

Fig. 15.

Welding of thick butt-welds.

the centre welds are executed after the side ones in order to reduce shrinkage stresses. Defects arise more easily with narrow weld than with layer welding and it would seem wise to adopt the lines followed by tank builders. Special measures might be introduced to reduce the tension further (Section 7 b).

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[7] *E. Höhn:* a. a. O. Footnote.

[8] *Joellenbeck:* Electric Welding *8* (1936).

d) Shrinkage Stresses in fillet weld joints.

When making fillet welds, only the surface of the parts to be connected are fused and no great penetration is necessary. Expansion and contraction of the weld material take place to the accompaniment of opposing tendencies in the longitudinal and transverse directions caused by the material at the sides and under the weld bead. When making a weld on the surface of a metal plate, tension conditions as shown in Fig. 16 will occur in the longitudinal and in

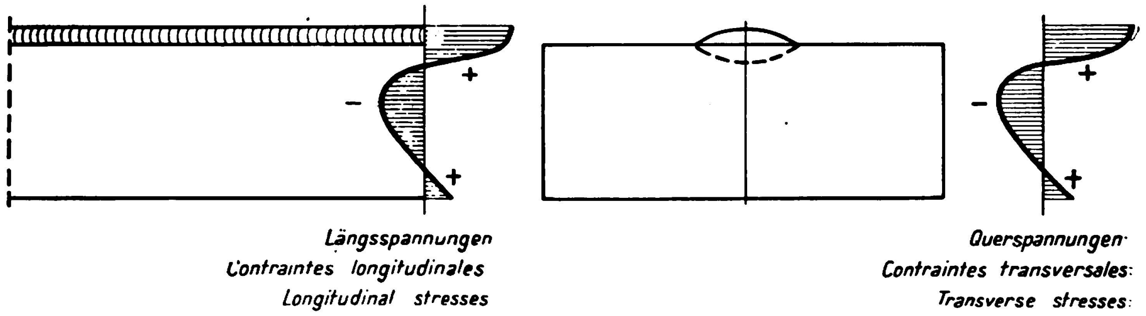

Fig. 16.

Longitudinal and transverse stresses produced by a weld.

the transverse directions, and here the maximum tensile stresses in both directions will correspond at least to the ductile limit of the material. In addition to this bi-axial stress with high longitudinal and transverse tension, there is an intense vertical tension resulting from the shrinkage stress of the two parts which are assembled. In any case the zones in the neighbourhood of all the adjacent surfaces of penetration and probably the greater part of the seam are subjected to a high degree of spacial tension coming from all sides (Fig. 17).

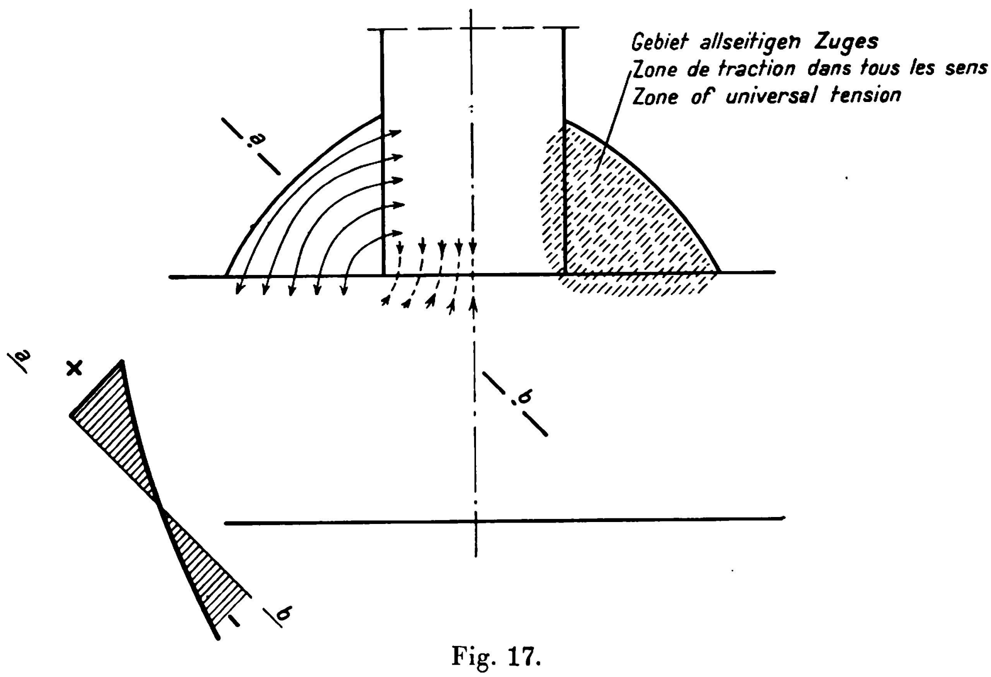

Fig. 17.

Shrinkage effects of fillet welds.

The shrinkage stress set up in $\perp$-shaped connections can be reduced by carrying out the two parallel welds one after the other and for this reason, when making long welded joints, the two welds are often zig-zag welded. When using fillets for welding plates on to structural members arrangements should be made to increase the spaces between the welds.

Fillet weld joints are more liable to crack than butt welds. This is because of the conditions of actual tension which are far less favourable. These somewhat brief statements will be supplemented in the following Section, which deals in a general way with this same problem.

6) Risks of cracking.

Cracks may occur directly after welding while the metal is still hot and during cooling at the temperatures of decreased deformation capacity, that is, at about 200 to 300° C. (zone of blue or temper heat of fracture). It appears doubtful whether cracks can result from weld stresses even after cooling unless there is some additional stress exercised from without. Probably in most cases the cracks which have occurred were caused by high temperatures; even cracks that appeared only after welding were perhaps started while welding was proceeding. (No account is taken here of cracks in tacked parts nor of those in the welded joints which occur when other parts of the joint are being welded.) In many cases cracks were recognized as being definitely due to heat effects ($t \geqq 600^{\circ}$ C).

It is therefore necessary to base estimates concerning risks of cracking and decisions providing precautionary measures mainly on the behaviour and the properties of the weld material at high temperatures. Consideration of the state of tension observed when the metal has cooled down can easily lead to erroneous conclusions. Weld metal used in this connection should be interpreted as being the mixture of melted welding rod and the melted parent metal.

The thermal coefficient of expansion for steel at indoor temperature is $1.1.10^{-5}$ (per degree); above 100° this figure increases gradually. The entire shrinkage of the weld metal (melted rod and melted parent metal) when contraction proceeds freely and when cooling has brought the metal from 700° C to indoor temperature is about 1 per cent. When clamping exists there is an additional shrinkage due to the obstruction of the neighbouring zones which have been heated to a higher temperature; the extent of this shrinkage depends on the various structural conditions (degree of tension) and on the welding conditions *Wörtmann* and *Mohr*[9] have published further detailed information on this matter, laying down a figure of 4—6.5 per cent. for the entire contraction in a specific case where circumstances were very unfavourable. As for the coefficient of elongation of the melted welding rod, with the rods commonly used nowadays, this figure could be considerably exceeded, particularly for high temperatures, and it would then be hard to explain the presence of cracks.

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[9] *F. Wörtmann & W. Mohr,* Calorific Stresses in Welds and Influence on Safety Factor in Finished Structures. Swiss Building Review, Vol. 100, Pp. 243/246.

For the production of diagonal joints on plates 12 mm thick (unalloyed steels and steels up to those with high carbon content) ($\leqq$ 0.7 per cent.). *Zeyen*[10] laid down that risks of cracking while in the hot state existed when using $C > 0.4$ per cent., together with heavily coated electrodes E 52 h (specification of the German State Railways). On the other hand when using lightly coated electrodes and alloy-core electrodes which mostly have a lower angle of flexure and less resiliency, risks of cracking at high temperatures disappeared. These phenomena can doubtless be explained by the fact that the amalgamation of the two last-mentioned rods with the basic metal was less intimate and therefore better in this case than the heavily coated electrodes. Thus the rods which generally were unsatisfactory from the point of view of deformation were found more suitable in special circumstances.

When weld stress occurs, the tensile state is always of a duo-axial and most often, particularly with fillet welds, of a tri-axial kind, and this is why resistance to thermal ductile limit and the coefficient of elongation, which are determinate quantities in the uni-axial state of tension, cannot serve as a criterion for gauging crack-proof qualities. As it is scarcely possible to obtain enlightenment concerning the standard internal state of cohesion of the mixture of electrode and parent metal at high temperatures and under the stress in question, there is no choice but to resort to empirical methods and experiment on tendencies to crack. See Fig. 1. When this type of experiment is made, a general picture is obtained of the properties of the material and the moulding capacity of the melted weld metal. It is my opinion that in this connection the problem of shape plays no small part in influencing the course taken by the forces of shrinkage.

With reference to the fillet welds shown in Fig. 17, if the triangular seam is limited by straight lines, the main lines of tension may be expected to follow an unrestricted course owing to shrinkage forces. Where joints are definitely concave, there will be an interruption of the course of the flow of forces near the surface with corresponding peaks of stresses (Fig. 18). This is why concave welds break more easily than seams of more or less triangular section. Incipient cracks which appear so frequently at the ends of hollow craters might very easily be largely due to this fact. The marked preference for hollow or grooved seams, resulting from a knowledge of their dynamic behaviour, should be restricted as far as possible because of shrinkage effects, and this is all the more desirable because, in the case of alternating stresses, the concave weld surface is a less important factor than the gradual transition from surface of the metal plate to surface of the weld, and with regard to certain stresses (shear welds) the importance of this aspect should not be unduly exaggerated[11].

When dealing with this kind of tension in connection with butt welds the shape of the various runs or layers of weld metal is of importance, because if the weld bead has a wrong shape cracks will be induced more easily than where the reverse is the case, even if all other conditions are equal (Fig. 19).

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[10] *K. L. Zeyen:* Welding of Unalloyed Steels of Great Strength. Steel & Iron *56* (1936), Pp. 654/657.

[11] *G. Bierett:* Design and Execution of Welded Structures Based on Research Work Concerning Tension and Resistance. Electric Welding *6* (1935), Pp. 141/150.

If the welds are too thin compared to the thickness of the basic metal, and this is particularly so in the case of the first layers run into the joint, cracks will occur very easily. When butt welds are being made a first layer which is too thin compared to the

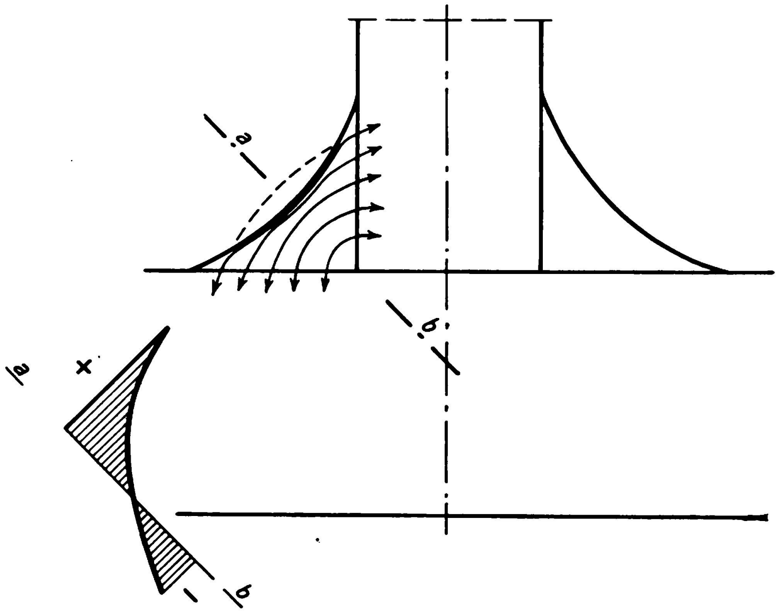

Fig. 18.

Shrinkage effects of distinctly concave fillet welds.

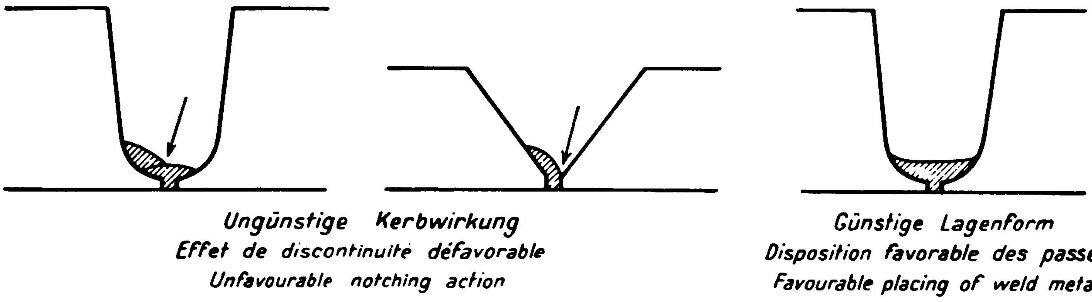

Fig. 19.

Danger of cracking when shape of weld unsuitable.

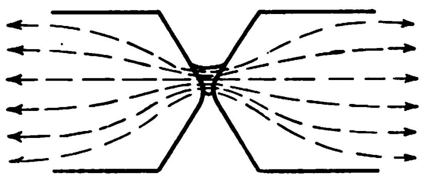

Fig. 20.

Endangering of weld-roots due to unfavourable flow of forces.

somewhat heavy plates will generally break under the tension present, because the flow of forces alone is a very unfavourable one (Fig. 20). Most cracks start at the root of the weld and that accounts for the common practice in tank construction of strengthening the first layer run into the joint and the thin portion of parent metal below by diagonal reinforcing straps placed at the rear of the weld (Fig. 15). In order to avoid the occurrence of cracks in thick seams, welding should proceed without any interruption until the groove has been filled up to a certain height. When welding first on one side and then at the back by turning the whole job round, a certain height should be reached in the groove before going on to the other side. When welding plates[12] around the whole circumference and using St. 52 as basic metal, it was found that the formation of cracks could be prevented by welding over the whole width of the seam (made in several layers) for each individual section welded, before passing on to the next section.

With fillet welds in which the first layer was too thin as compared to the thickness of the work in hand, cracks occurred in nearly all cases. When carrying out thin welds the part to be welded on to the structure was not sufficiently heated and its plastic properties did not extend deep enough, with the result that the stress effects were very great (Fig. 21).

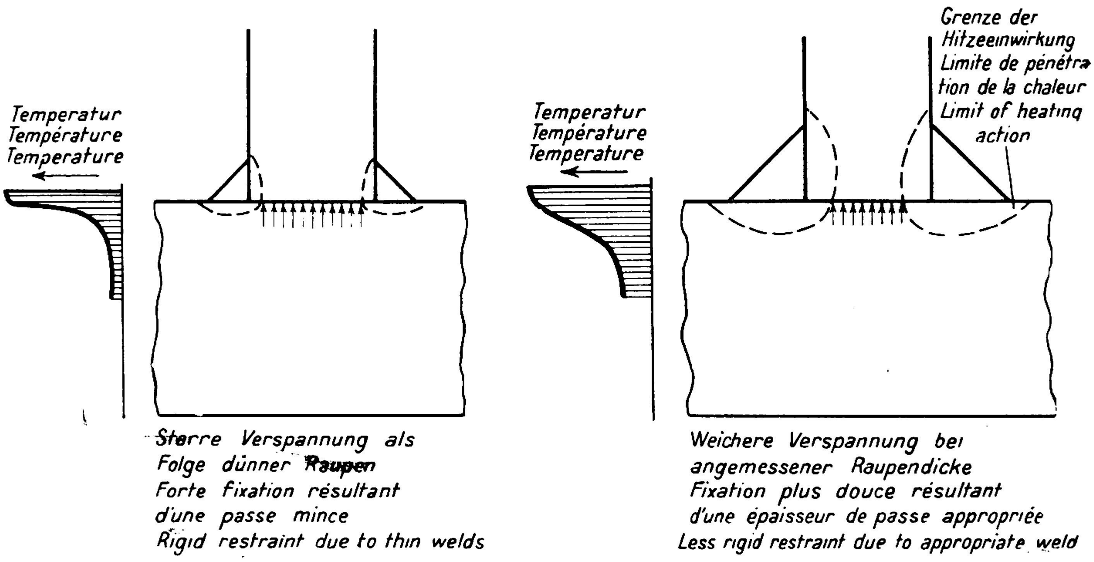

Fig. 21.

Restraint action of fillet welds.

When welding unduly thin beads to heavy pieces of metal the quenching effects were so great that with highly resistant steels, it was found that the zones of penetration exposed to tri-axial stresses had cracked. When this occurs the weld will be found to peel off the basic metal.

The thickness of the weld must be in proportion to the thickness of the material and in no case too small. (This is a point which should also be noted when leak-proof joints are being made on heavy members.) The instructions concerning conditions previous to welding when using thin rods must not be interpreted too narrowly.

In girder construction difficulties of the kind described may be largely avoided in connection with the collar welds by using spe-

[12] *H. Bühler & W. Lohmann:* Contribution to the Problem of Weld Stresses. 3. Cont. Actual Stresses in Welded Patches. Electric Welding *5* (1936), Pp. 221/229.

cial sections, such as "nose sections" (Union), bulb iron sections (Doernen) and S.T.-sections (Krupp). The main advantage of all these sections lies in the fact that the less massive parts which are rolled, namely: nose, bulb or web, increase heat maintenance and prevent unduly rapid cooling. In order to prevent cracking, these or similar sections should be used and this should be done increasingly where the metal is thicker or stronger.

7) Special Measures to reduce Stresses and Risks of Cracking.

a) Thermal Measures.

Special thermal measures can be applied during and after the operation of welding. They aim at preventing cooling proceeding in a similar way to quenching, reducing the danger of cracking while welding is being carried out, inducing more equable stress conditions along the length and across the width of the seam and reducing the longitudinal stresses in the zones of the weld. According to circumstances, one or other of these points will be more important and thus the thermal measures which are applied must be in keeping with these circumstances.

1. Preheating should be carried out when massive parts are being welded, and particulary in the case of hard steels, before the first layer is run into the joint. Steel structural engineering should make greater use than it does at present of pre-heating for weld seam edges or penetration surfaces. Where the weld is unilateral, for instance, when making a ⊥-section, more intense pre-heating may result in the metal at the final stage presenting no defective curves.

2. Heating of the sections of the weld which have been finished while welding of the later sections is still proceeding may reduce the stresses in long joints and in thick ones, with the consequence of reduction of crack occurence[13]. When making long seams which are welded without interruption, it is advisable to aim at obtaining a more even field of temperature by heating the welded joint after completion; in particular this should be done to the first layers run into the joint as these are particulary exposed to crack formation.

When making thick seams which are exposed to external or internal stresses, particularly those susceptible to cracking on account of the thinness of the first layers (Fig. 20), contraction may be prevented by keeping up the temperature of those layers by subsequent heating, and this should be continued until the seam has been built up sufficiently to resist stress. In the case of very thick seams the welding operator should heat the rear side subsequent to welding, and this should suffice to reduce stresses in that part of the weld. Meanwhile, it is quite likely that these very beneficial measures have been rarely applied so far.

Where these intense stresses are present the zones neighbouring on the welds can be heated while welding is proceeding.

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[13] *G. Bierett:* Application of Knowledge Concerning Stresses to Working Methods when Making Butt Welds for Steel Structures. *9* (1936), Pp. 69/71.

The thermal measures mentioned above serve to prevent cracking while welding is being carried out. However, it is not very likely that the remaining average transverse stresses will be less than where additional heat is not applied; it is more probable that the reverse will be the case. To counter-balance this, however, mechanical measures — in particular, hammering — can be resorted to (Section 7b).

3) Heating subsequent to welding can be applied in order to equalize any very marked uneven stress conditions within the weld seam, either along it or across it, in order to reduce the longitudinal stresses very considerably. When external stresses or some similar condition exists (welding tests, patching, for instance), there is no certainty that the average transverse stresses will be reduced. A very useful means of combatting unequal tensions can be obtained by heating the metal to a deep red glow[14]. Subsequent heating of lines along the welding zones at temperatures of from 550 to 600° C. may reduce the longitudinal stresses in the welds very considerably[15]. This method has been applied when welding very heavy tubes[16]. This intense heating may, however, induce greater warping, and the methods should therefore be used with great care.

Generally speaking, intelligent application of heat will result in improved quality of the weld. Methodical application must, however, be based on expert knowledge.

Welders should be warned against employing measures to accelerate cooling or to maintain the parts to be welded cool by artificial means. Such means may, as a matter of fact, prevent bending or warping, but they generally increase the stresses. Heat should be allowed to escape from the welded joint and to pass through the parts to be joined without any artificial means. (Special cases in which artificial cooling is useful and has no deleterious effects hardly arise in steel structural engineering.)

b) Hammering.

The welds, or the zones in the neighbourhood of the weld are hammered. This is done either when the metal is red hot or when it is cold.

Hammering when the weld is red hot necessitates having malleable weld metal. In the past this method was mostly applied for gas fusion welding only, but it is now used for electrically welded butt welds. Its aim is not to reduce stress but to make the joint more leak proof; it is also used in connection with correcting defects such as sag or bend. Hammering the zones near the seam while ie a red hot state relieves an unfractured weld under great stress; as far as I know, it is not much applied in steel structural engineering.

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[14] *G. Bierett & G. Grüning:* Shrinkage Stresses in Oxy-acetylene Welded Parts. Autog. Metalworking. *27* (1934), Pp. 259/266.

[15] *Ebel & Reinhardt,* Measurement of Stresses in Welded Circular Seams. Autog. Metalworking. *27* (1934). Pp. 305/310.

[16] *R. Schmidt:* Observations on the Problem of Heat Treatment Subsequent to Welding when Engaged on Large-scale Jobs. Electric Welding *6* (1935), Pp. 231/232.

Cold hammering of the joint requires above all suitable weld material which will not be liable to microscopic cracks or to brittleness. Hammering of welds reduces longitudinal and transverse stresses and when the zones neighbouring on the weld are hammered the idea is to reduce transversal tension. With thick weld seams intermediate layers are inserted so as to prevent excess tension and bending; these are hammered into position in the centre of the weld.

Hammering also calls for expert knowledge concerning the materials being used.

Summary.

Welding is a complicated metallurgical process. The occurences which take place when the welding zones are cooling lead to the formation of cracks when material of a certain composition or of unfavourable cooling speed is being used. The parent metal and the welding rods required in steel structural engineering must consequently be selected for their crack-proof qualities. Welding rods which produce weld metal tending to crack should be eliminated right from the start by appropriate tests carried out previously, and the same applies for rods which melt too rapidly when undue heat is applied.

Weld material, if its movements are unrestricted, contracts uniformly in all directions. Practically, this possibility of unhampered movement is present only in the transverse direction and then only in butt welds which have been executed with great rapidity. The extent of the transverse contraction depends on the size of the section of the weld and the specific heat consumption of the welding rod, and this should therefore be as limited as possible. Alongside the transverse contraction angular contraction takes place in the thicker welds; its extent depends mainly on the shape of the section, the size of the weld and on the number of weld layers made. Transverse contraction is lower in fillet welds than in butt welds. Longitudinal contraction is always less intense than transverse contraction as not only the expansions of the heated zones, but also the shrinkages in this direction are hampered by the colder zones. This obstruction causes intense longitudinal contraction, the size and course of which, on both sides of the joint, depend on the width of the zone of heating. Reasons connected with equilibrium cause longitudinal stresses to be always followed by transverse stresses; this means that it is not possible to weld without inducing transverse stresses. Intense compressive stresses are set up at the ends of the weld joints, transversally to the welded seam, and in the centre tensile stresses arise. This state of transverse stress is also found in the neighbourhood of welds of medium length and great depth.

The longitudinal shrinkage stresses are of particular significance for the welds which run uninterruptedly in the main direction of forces. As the longitudinal weld stresses are very intense, it is advisable where welds are under tensile stress to avoid unduly narrow heating zones, as these set up particularly intense stresses in the weld. On the other hand, with structural members exposed

to risks of bending, great care should be taken to keep down the compressive stresses of reaction which maintain equilibrium of the longitudinal weld stresses; this can be effected by restricting the weld sections and by executing the weld with as limited an amount of heat as possible.

When making a weld, transverse stresses of more or less intensity are practically always set up. A distinction must be made in this connection between external and internal stresses. The external stresses depend on structural conditions. The parts to be welded together are fixed before beginning to weld. The internal stresses of a weld are due to the fact that melting, running the weld metal into the joint, heating and cooling of the various parts of the joint cannot be done in one operation but have to be carried out successively. Intense stresses are set up in fillet weld connections and when welding plates into or onto larger members.

One of the main conditions underlying the reduction of external and internal stresses is that of keeping down the dimensions of the weld sections, and the elimination of welding rods which require an unnecessarily large specific heat supply. Stresses of the external kind are reduced most effectively by elastic shaping of the parts adjoining the joint, and by appropriate sequence of the various welds. Prevention of shrinkage, for instance, by friction resistance of massive parts, can be eliminated by measures which encourage the proces of contraction. Internal stresses in a weld seam above the length and height of the seam must be combatted above all by increased welding speed, sequence of welding operations and avoidance of too many layers.... Continuous non-interrupted welding is advantageous when making long welds and above all when running the first layers of weld metal into the joints as this latter is especially prone to cracking. The stresses at the top of the weld can be reduced by giving the joint a symmetrical form and by alternately welding front and back of the joint and by limiting the number of layers.

Conditions governing weld stresses are far less favourable for fillet welds than for butt welds, as the zones of welding are exposed to intense tensile stresses on all sides. The two joints of ⊥-shaped connections should be welded one after the other, the length of expansion between the two parallel fillet welds should not be too short if contraction is to be reduced. As a general rule fillet welds are more liable to crack.

As a rule the cracks occur while the material is hot and during cooling in the zone of temperature in which the coefficient of deformation is lower. (Zone of tempering fracture.) Gauging the risks of cracking and providing measures to prevent this must therefore be based mainly on the behaviour and properties of the weld material at high temperatures. The coefficient of elongation for the uni-axial state is of no use as a criterion for gauging the risks of cracking. Appropriate tests must therefore be carried out in order to determine the crack-proof qualities of the material. The shape of the section of the seam plays some part in ensuring safety against cracking. Definitely concave welds break easily compared with seams of approximately triangular section, as in the case of the concave welds unfavourable conditions of actual stress arise. Welds with marked notches tend to crack easily. Welds that are too narrow in proportion to the thickness of the material, and in particular, layers at the root of the weld which are too thin lead easily to cracks. For this reason the thickness of the weld must be in keeping with the thickness of the material being used. When making thick butt weld joints the welding must proceed without interruption until the joint is fairly well filled. In girder construction the carrying out of the collar welds can be facilitated by using specially rolled sections.

Special heat treatment, prior to, during and after welding, aims at preventing cooling of a quenching nature, and also at reducing risks of cracking while welding is proceeding. It is also applied in order to obtain more equable tensile conditions along and across the weld and to reduce longitudinal stresses in the welding zones.

Cold hammering of the weld can only be done with weld metal that does not tend to form microscopic cracks and does not incline to brittleness when hammered. Hammering is a useful means of reducing stresses left in welds after the welding has been terminated.