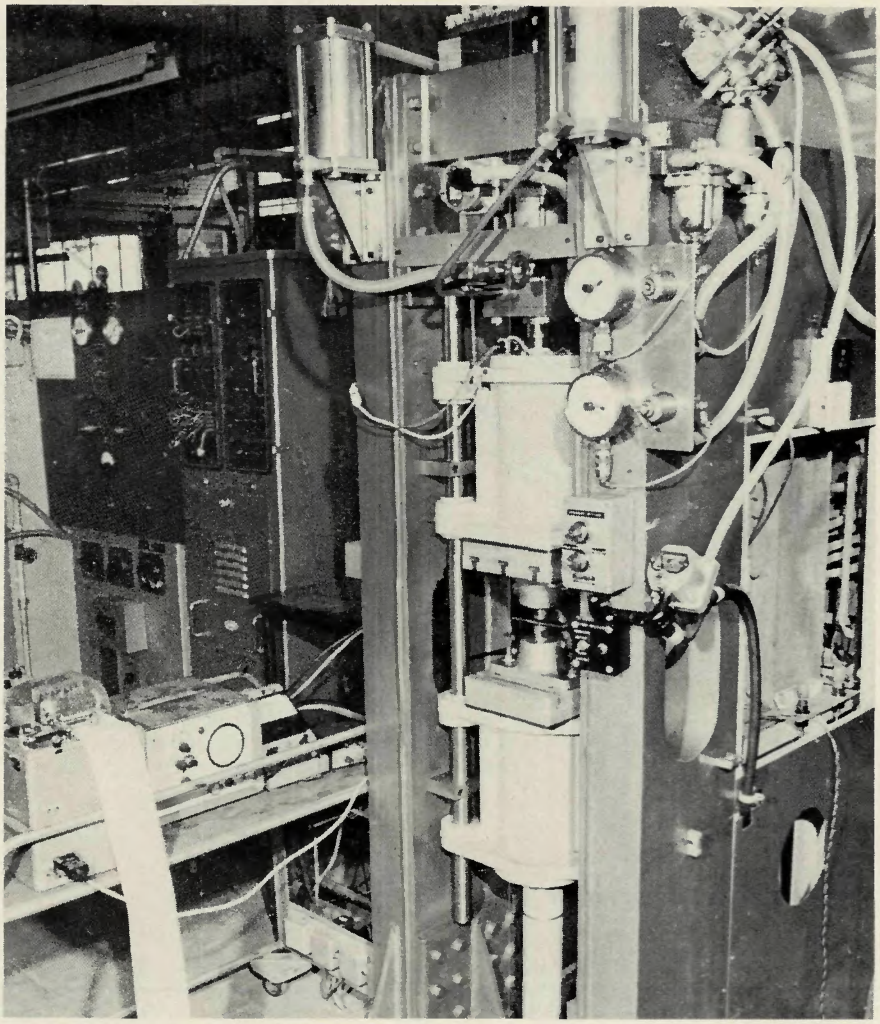

New Design of Resistance Spot Welding Machine for Quality Control

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Since, at a given current and weld duration, the electrode load affects the final nugget size, the load value can be used to regulate nugget development and compensate for variations in effective heat input. Weld expansion (electrode movement apart) is an index of nugget development and can therefore be utilized as a suitable sensor to control the electrode load

ABSTRACT. The effect of electrode load on the growth of the weld nugget in resistance spot welding has been investigated for 0.9 mm (0.036 in.) and 1.6 mm (0.064 in.) mild steel sheet using a specially constructed low inertia, rigid experimental machine. It has been shown that spot welding can be made tolerant to variations in welding current and time by automatically controlling the electrode load as a function of the weld expansion (which is an index of weld nugget development).

The performance range of this self-load control has been examined for a simple system in which the electrode head is brought into contact with the work and thereafter restrained, so that as weld expansion occurs, the electrode load increases according to the stiffness of the machine frame (locked head system). The results show that under these conditions there is an appreciable increase in tolerance to variations in operating current and weld duration.

The range of tolerance can be further increased by using a more complex compound restraint self-loading system. This system employs a low initial stiffness which is considerably increased (with expansion) towards the end of the weld period. The restrained head technique gives adequately sized welds in spite of a welding current variation of +15%, −20%, while normal welding machine conditions give acceptable welds over a range of only ±10% in 1.6 mm (0.064 in.) material. Similarly, compound restraint gives adequate welds when the weld time is varied by +100%, −50%, while normal operation only gives acceptable welds at +40%, −25% (8 cycle weld).

A compatible monitor system for weld quality assurance is also described which utilizes the increase in load for the restrained head system to confirm that a nugget has been established.

The scope for industrial application of the locked head system is briefly discussed and designs outlined for obtaining locked head characteristics on welding machines of otherwise conventional design.

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Introduction

In resistance spot welding, two sheets are brought together, held under pressure between two electrodes and a high current passed via the electrodes through the workpieces for a short time to heat the interface sufficiently to form a common weld nugget. In normal practice the applied load, welding current and weld cycle duration are preset for a particular application, depending on the material to be welded and on the diameter of the electrode tips. These external parameters are, as far as possible, held constant both from one weld to the next and during the formation of any one weld. In particular, care is taken to ensure that the electrode head moves freely in its guides so that the electrode load is constant and not upset by stiction and the like.

However, even when the main variables are held constant, there is often considerable variation in weld size or quality due to such factors as changes in the surface condition of the workpieces, electrode wear and the shunting effect of alternative current paths through adjacent spots. For this reason monitoring the quality of the weld or control of the development of the nugget is highly desirable. In the past, several monitoring techniques have been proposed[1] and in addition in some cases a feedback control has been developed in which the monitored parameter is used to sense the development of the nugget and to operate on one or more of the main variables so as to maintain a desired nugget size.[2, 3] In the weld control systems proposed previously the sensing parameter had been arranged either to operate on the welding current, or to determine the weld cycle duration, or both with a substantially constant electrode load.

Owing to the expansion associated with the thermal heating of the material to be welded, including the formation of the liquid nugget, the welding electrodes are, under normal conditions, forced to move apart. Typically using electrode tips 5 mm ($^3/_{16}$ in.) in diameter, this expansion (head movement) amounts to about 0.2 mm (0.008 in.) for steel sheets 0.9 mm (20 swg) thick, and about 0.3 mm (0.012 in.) for steel sheets 1.6 mm (16 swg) thick.

This paper considers the possibilities of controlling the weld nugget by means of the electrode load and in particular of basing this control on the head movement (patents applied for). In the simplest arrangement the expansion directly governs the load applied, according to the rigidity of the welding machine. For this the electrodes are brought together into contact with the work, and then locked or restrained to prevent their free movement apart. The attempted expansion of the weld nugget then results in a corresponding increase in the applied load. This is termed a 'locked head' system to differentiate it from conventional resistance welding equipment in which the moving electrode is relatively free.

Principle of Automatic Weld Correction by Electrode Load

Effect of Load on Nugget Formation

The new correction method is based on automatically varying the electrode load during the weld cycle and in

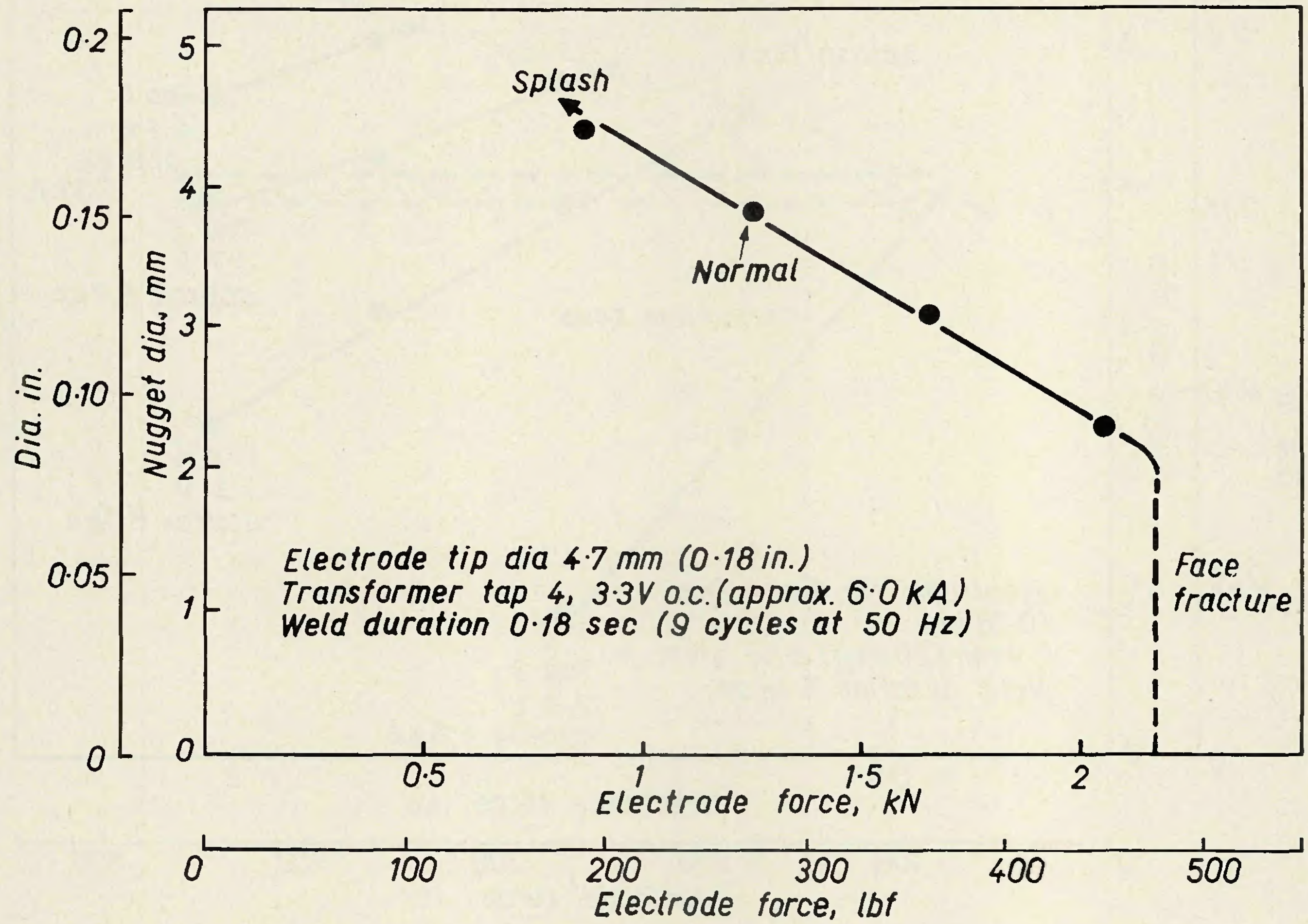


Fig. 1—Effect of electrode load on nugget diameter for 0.9 mm (20 swg) mild steel

particular with controlling the load as a function of the development of the nugget by means of the associated expansion. That the electrode load or pressure is significant in resistance spot welding is well known and for consistent welds in mild steel it has been recommended that the pressure be maintained constant within ± 15%.[3] Thus for a given material and thickness, particular combinations of weld current and duration are established by trial and error for a predetermined electrode load which itself is based on the tip diameter which in turn is related to sheet thickness.

The effect of variation in electrode load on nugget development with otherwise constant welding conditions is illustrated in Fig. 1 for 0.9 mm (20 swg) mild steel. [In these tests the degree of phase shift (heat control) is constant but the current can be varied by altering the transformer tap.] The current at a given voltage tap setting is nominally constant but does increase by 2 to 3% from a low to a high electrode load owing to the decrease in interfacial resistance.) At a given current and weld duration the nugget size increases with decrease in electrode load until weld splashing occurs; while on the other hand with increase in load the nugget size decreases until a face fracture sets in. With further increase in load the nugget size rapidly becomes insignificant resulting in a stuck weld which has no strength.

The mechanisms by which electrode load affects the nugget development are believed to be threefold. First, with increase in load the interfacial resistance decreases and hence the initial heating at the interface is reduced at the early stages of the weld duration.[5] Secondly the electrode contact with the work is improved at higher loads and the current distribution from the electrode tip into the workpiece is modified giving a lower current density and hence a reduced effective heating. Finally, particularly with thin sheet, the increased electrode load results in increased heat conduction from the workpiece to the water-cooled electrodes.

These three factors act in the same direction and hence the nugget development is reasonably dependent on the electrode load. Thus, as shown in Fig. 1, the change in nugget diameter with load is approximately linear between the limits where weld splashing sets in and where the nugget decreases very rapidly in size to leave a low strength or face fracture condition. In this case a change of 25% in electrode load results in a 10% change in nugget diameter for a well developed nugget which is approximately the same size as the electrode tip.

Similar nugget diameter/electrode load relations can be found for other welding currents, as shown in Fig. 2 for 0.9 mm (20 swg) mild steel. In this case the weld heat is altered in relatively large steps by changes in the transformer primary tapping, giving open circuit voltages ranging from 4.1v to 2.8v or broadly +25% to −15% of the normal condition (transformer tap 3.3v). As can be seen from Fig. 2 there is a correction zone for 0.9 mm (20 swg) mild steel where, in spite of current changes from about 5ka to 7ka, a substantially

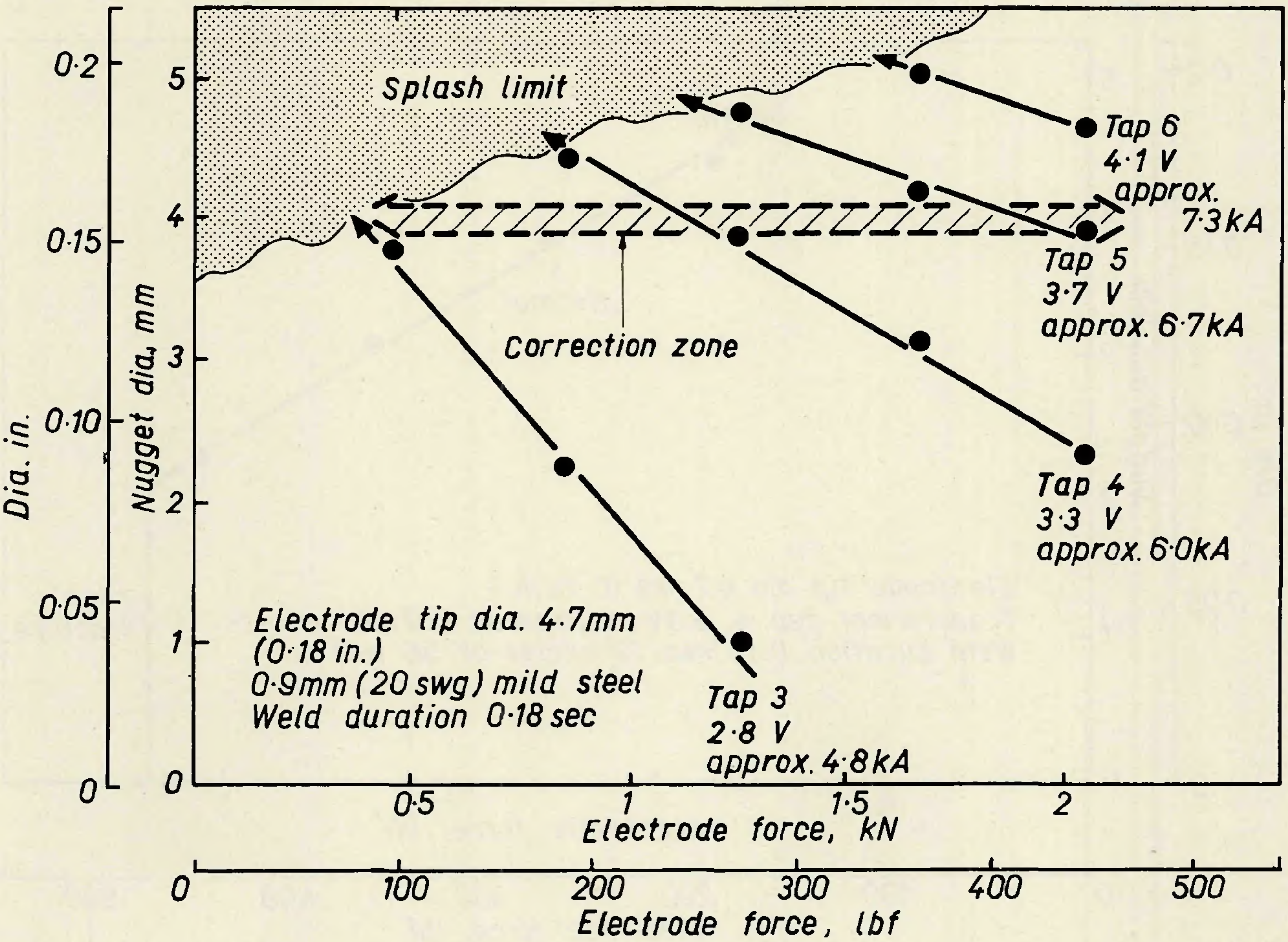


Fig. 2—Principle of weld correction by electrode load to compensate for heat variation in welds at constant durations

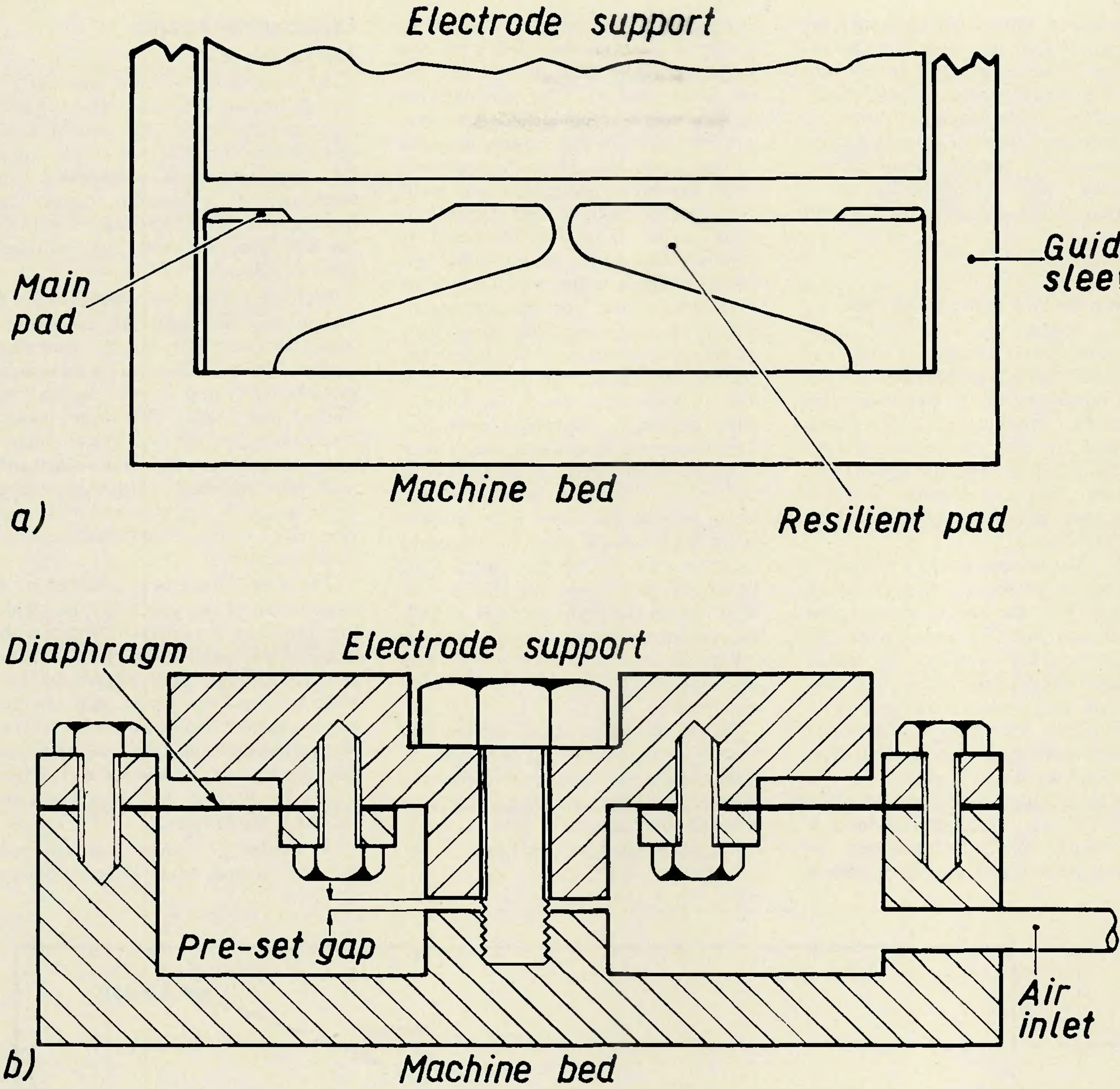


Fig. 3—Typical oscillograms of weld current, electrode load, and head movement for free and restrained electrode systems: (a) conventional machine with nominally constant electrode load; (b) locked head machine with electrode load dependant on weld expansion

constant nugget diameter of around 4 mm (0.15 in.) could be maintained by varying the electrode force from 0.5 to 2.0 kN (about 100 to 450 lbf.) Thus in effect a constant nugget is obtained for a range of $\pm 15\%$ in current by changing the electrode load in accordance with the transformer tap setting or weld heat control.

Principle of Self-Load Correction

As already indicated above the nugget size could be maintained within reasonable limits by automatically changing the electrode load as a function of the welding current or as a function of the supply voltage. This requires *a priori* knowledge of the relation between say the mains voltage and the nugget diameter as a function of electrode load. But variation in the supply voltage is not the only cause of variation in nugget size since, for example, the effect of current shunting due to an adjacent weld results in a reduction in the nugget formed with a given transformer voltage and heat control setting. Therefore a control method is required which senses the development of the nugget and which then changes the electrode load so as to regulate the final nugget size. Thus, if the nugget is not developing rapidly enough, the electrode load is reduced; and conversely, if the nugget is tending to splash through over-development, the electrode load is increased to contain it.

One method of achieving such control is to use the electrode movement or rate of expansion (which itself is well correlated to the nugget development) to regulate the applied load. Since the weld durations are short (typically less than 0.2 sec) it is difficult to accomplish the necessary load changes via an external servomechanism which operates on the piston cylinder pressure. On the other hand, on a rigid welding machine the frame itself represents a high rate spring of the order (as measured) of some 10 kN/mm (55 lbf/mil); in other words, some 2 kn (450 lbf) for 0.2 mm (0.008 in.) which is the expansion to be expected from 0.9 mm sheet mild steel under normal conditions. Thus, if the machine frame and electrode support were sufficiently rigid, it would be possible to control the electrode load automatically as a function of the expansion in the weld zone.

Welding Machine With Locked Head

To obtain the desired load-expansion characteristic it is necessary to prevent as far as possible any reverse movement of the electrode after it has been brought into contact with the work, so that the attempted weld expansion reacts directly against the machine frame. (Possible arrangements for practical application are discussed later.)

For the present work a relatively rigid bench welder was used in which for simplicity the electrode head was locked into place by means of wedge blocks mounted between the platen and the cylinder head. The characteristics of this system compared with conventional operation is illustrated by oscillograms of weld current, electrode movement and load.

Under normal conditions of operation, Fig. 3a, the electrode load is substantially constant throughout the welding period and expansion freely takes place. The rate of expansion, which is closely associated with the nugget growth, depends strongly on the weld current. The comparative oscillograms for the locked head system are shown in Fig. 3b for the same current conditions. Here the electrode load increases throughout the weld cycle as a result of the expansion. (The actual expansion registered is impoverished, owing to the deflection of the machine frame which serves as a reference base for the expansion transducer.) It should be noted that, owing to the increase in load that occurs, the initial load at the beginning of the weld cycle is much lower than normally employed, otherwise the increase in load would result in a much reduced nugget compared with the freehead situation. It is also interesting to note that there is no tendency to weld splash early in the weld cycle in spite of the low initial load employed. In addition any tendency to weld splash at high currents, which are accompanied by a high rate of expansion, are suppressed by the major increase in electrode load which also results.

In use the locked head system was found to be reasonably tolerant to weld current variations and to changes in weld duration and compared with conventional operation gave a more consistent nugget as described in detail below.

Experimental Results

Test Technique

Single spot welds were made in 25 mm (1 in.) square coupons of 0.9 and 1.6 mm (20 and 16 swg) mild steel of specification En 2ACR3 (0.1% max C) using standard replaceable tip electrodes of chromium copper to specification RWMA Class 2 with a flat tip face and 120 deg included angle profile.

Welding current was measured by a toroid together with a resistance-capacitor integrator and the true rms current calculated from high speed records according to the method of Evrard and Hasle.[6] The head movement was registered by a linear inductance transducer and the electrode load also recorded using a standard strain gauge bridge attached to a load ring which directly supported the electrode assembly.

The weld current was adjusted by a coarse control tap switch on the welding transformer primary together with a fine heat control using phase shift to give an average sized nugget for the electrode and materials used under conventional conditions of operation. With this condition taken as the norm the response of the system was determined by altering the current and/or the electrode pressure.

A similar procedure was adopted for the locked head system, except

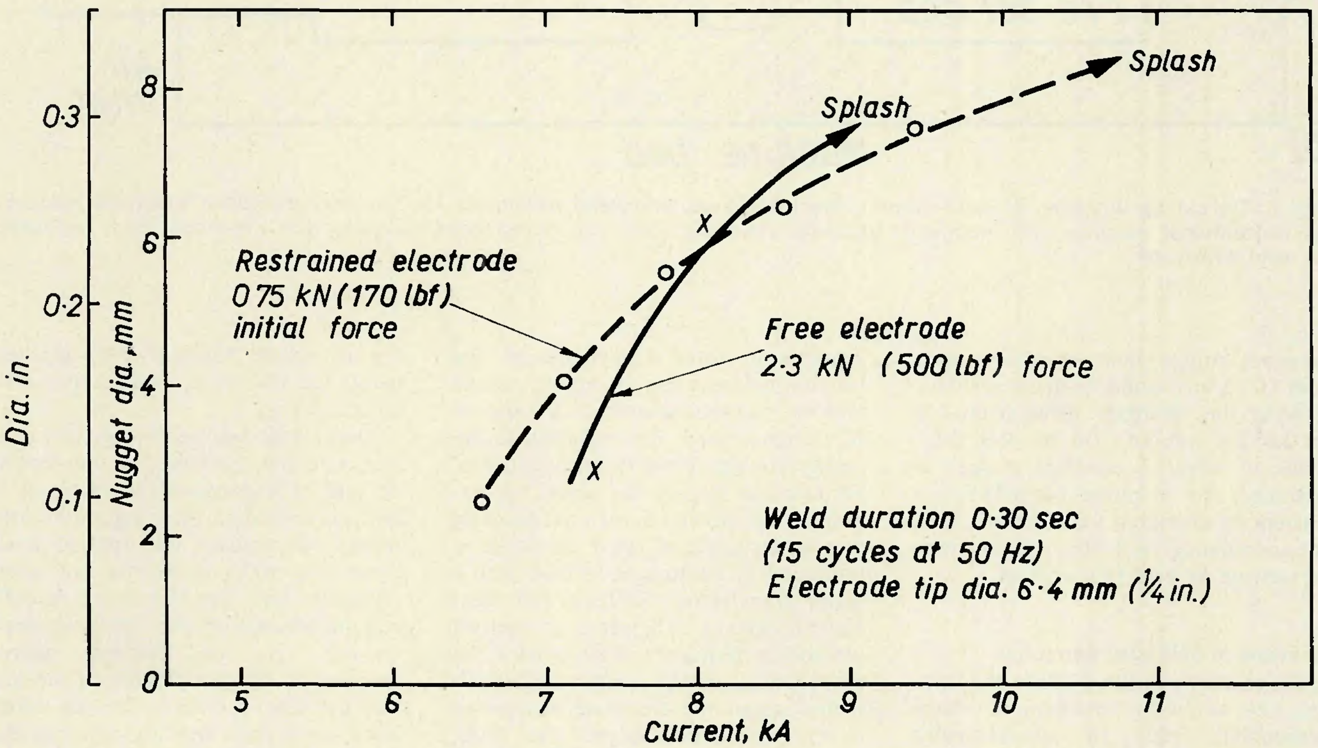


Fig. 4—Comparison of effect of weld current on nugget diameter with free and restrained electrode systems for 1.6 mm (16 swg) mild steel

that the initial load and degree of compliance were adjusted until a nugget corresponding to the norm was obtained at the previously established standard current. The transformer heat control and electrode pressure were then varied as before. In both cases weld samples were taken for metallurgical examination and slug diameter measurements were made from pulled test pieces.

Effect of Variation of Weld Current

Since the new system depends on expansion for the application of load, initially 1.6 mm (16 swg) thick mild steel sheet was used so that the expansion would be large compared with any backlash or other possible mechanical defects of the set up. For these tests the electrode face was machined flat with a 6.4 mm diameter tip and the weld duration maintained constant at 15 cycles (supply 50 Hz).

The results of varying the heat input (welding current) on the final nugget size are shown in Fig. 4 for both the normal free electrode and for the restrained or fixed electrode system. In both cases there is a range of nugget sizes depending upon current, up to a maximum limit where splashing occurs. However, the change in nugget diameter with current over a reasonable size range is significantly reduced with the restrained electrode system. In this case the factor of improvement is about twofold. For the locked head arrangement the range of permissible operating currents is some 7 to 10.5ka (compared with about 7.5 to 9ka), since the tendency to splash at excess current is suppressed by the increasing electrode load which occurs with the increasing electrode expansion.

Effect of Initial Load on Nugget Development

For the above tests the initial load in the restrained electrode system had been pre-adjusted until a similar nugget size was obtained at the heat setting (welding current) which had previously resulted in a well developed nugget for the normal free electrode system. Since the initial load is one of the variables in the restrained electrode system, its effect on nugget size was examined in further detail.

For these tests 0.9 mm (20 swg) thick mild steel sheet was used so the initial load would appear as far as possible as a main parameter, and not be outweighed by the effect of expansion.

As previously, the locked head system showed a distinctly greater tolerance to changes in weld current than the free head system. The main effect of increasing the initial force

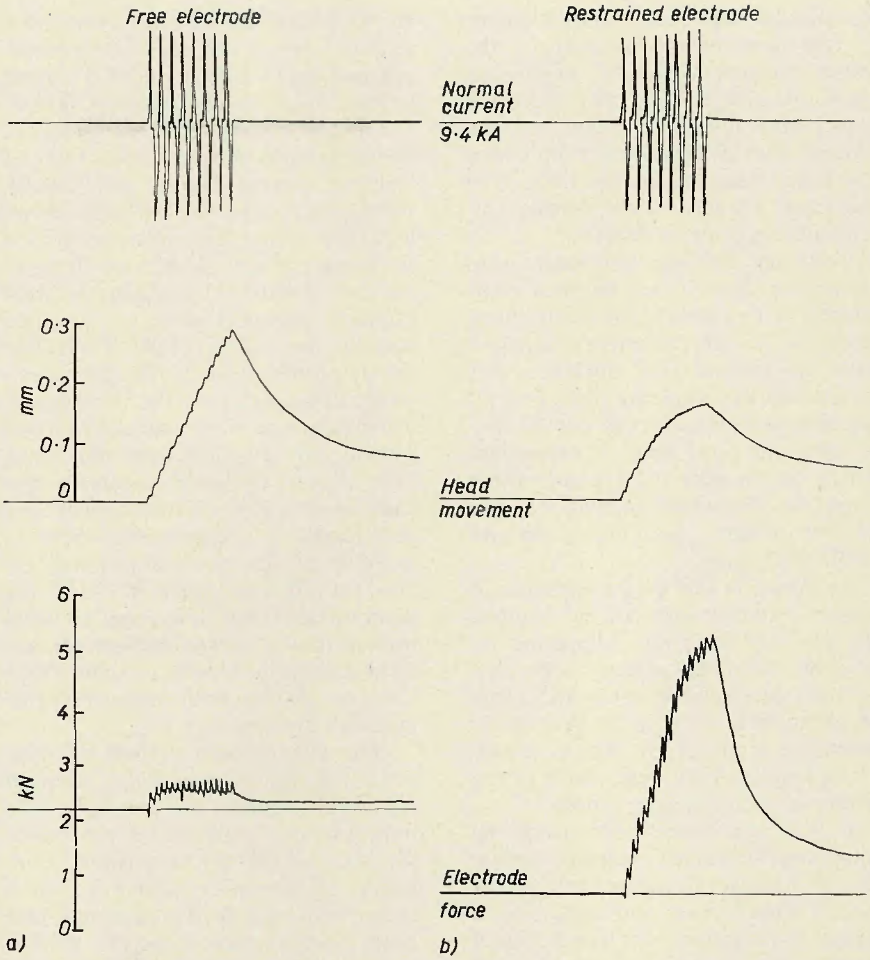


Fig. 5—Basic designs for dual compliance type of restrained electrode: (a) cantilever arm type load cell; (b) variable pressure diaphragm with limited movement

from 0.3-1.25 kN (70-280 lbf) was only to shift the nugget diameter-current relationship towards higher current levels without significantly altering the slope of the nugget diameter to current curve. However the initial load setting itself is not critical, and the requisite welding current for any given load condition can be established by a simple trial and error procedure as in normal practice.

It should be noted that even with very light initial loads (for example only the dead weight of the head) there is no tendency to splash although higher loadings allow a larger final nugget (and higher heat settings). The range of current (which is greater than for the free electrode system) is moreover similar for both the normal and the low initial load conditions. From this it would appear that a combined compliance, giving an initially low spring rate followed by a high spring rate, would be beneficial. Consequently at low currents, or where the effective heating is limited, the electrode load would be low to encourage as much nugget development as possible; whereas with high heat input conditions and a greater degree of expansion, the electrode load would increase rapidly and virtually prevent further nugget growth, as demonstrated below.

Dual Rate of Electrode Restriction

For these tests the Welding Institute Research Resistance Welding Machine was used since it has a very rigid construction and a low inertia-free head supported on linear race guides. Apart from the normal actuating mechanism, this machine was fitted with a lower electrode support which consisted of a low and high rate spring combination. A basic design for a dual compliance spring is illustrated in Fig. 5a, where initially the low spring rate is provided by the cantilever arms of a diaphragm type spring, which after a small degree of deflection are superseded by the high spring rate presented by the solid block in conjunction with the overall machine frame. For these tests, however, the variable dual compliance system shown in Fig. 5b was used. This is pressurized such that a preset degree of free movement is available to the lower electrode while the upper electrode remains locked. The electrode load is thus initially constant and low but for a weld expansion greater than the preset distance the electrode load increases sharply with further attempted electrode movement.

Tests on 1.6 mm (16 swg) mild steel sheet showed that the dual compliance system with a nominally fixed electrode is very effective compared with the normal free electrode. For these tests the weld duration was reduced to 0.16 sec (8 cycles at 50 Hz) to avoid the "roll over" in expansion, which sets in after 0.2 sec and which limits the maximum current that can be used without splashing at the end of the weld cycle.

As shown in Fig. 6a the variation of nugget diameter with current is much less sensitive using the compound restrained electrode system compared with a free electrode. Thus the range of permissible currents is very wide, extending from about 7ka to nearly 11 ka before either weld splash or the failure to form a nugget results.

It was also found that using the compound restrained electrode system the weld nugget develops early in the overall weld period and that after a nugget of reasonable size is established further development is considerably attenuated. For example, as illustrated in Fig. 6b, at a current which gives in 1.6 mm thick (16 swg) mild steel sheets a nugget diameter of greater than 80% of the electrode tip face diameter (viz. 5mm), variation in weld time has relatively little effect in the dual compliance system compared with the free electrode system.

With the nominally constant applied load (free head) there is, in the case illustrated, substantially no nugget formation for the first five cycles (0.1 sec) of current and only in the ensuing one or two cycles does a nugget appear. With the conventional system, the nugget is then fully established in the remaining two or three cycles of welding current before weld splash inevitably occurs. On the other hand, with the restrained electrode system the nugget is well formed by virtue of the low initial load early in the weld duration period and is of adequate size by the fourth cycle. Thereafter the development of the nugget is relatively slow, owing to the corresponding increase of weld load with nugget growth and a splash does not occur even after 15 cycles of current. In this case the overall tolerance in weld time is at least 0.15 sec, or some −50% to +100% of the mean duration 8 cycles (at 50 Hz) normally used. As demonstrated the tolerance to weld time with the compound compliance fixed electrode system is some three times better than with the normal free electrode system.

Also with reduced current the nugget still develops remarkably early in the weld period; for example, the nugget is well established at the end of the sixth cycle for a current 25% below the normal required for an 8 cycle weld with the conventional free head (with the free head the weld is still undersize even after doubling the welding time).

Thus with a suitably designed restrained electrode system it is possible to increase the tolerance to weld current variation and weld duration variation for mild steel sheet by a significantly large amount compared with normal practice. Furthermore these variations can be tolerated even when they occur in the same sense.

In addition there is considerable latitude in the initial load for the compound restrained electrode system which is maintained to a large degree even with significant changes in the weld current. An indication of the degree of tolerance is shown by the nugget diameter data given in Table 1 for 1.6 mm (16 swg) mild steel for a constant weld duration of 8 cycle (0.16 sec). Similar data is found for 15 cycle weld duration.

It should be noted that with the normal free electrode at the standard welding load the only combinations giving satisfactory nuggets are where the current and load increase or decrease together and that all other combinations shown in the table lead to underheated or overheated welds which for the more extreme combinations give stuck or splashed welds.

Table 1—Typical Nugget Diameters for Combined Variations in Initial Load and Welding Current for Dual Compliance System

Relative initial electrode load	Welding current, amp −15%	−10%	Norm. (~8.5 kA)	+10%	+15%
+30%	3.0* (0.12)	4.3 (0.17)	5.2 (0.21)	6.0 (0.24)	6.5 (0.26)
+20%	3.5* (0.14)	4.5 (0.18)	5.5 (0.22)	6.2 (0.25)	6.7 (0.27)
Norm. 75 kgf (125 lbf)	4.4 (0.17)	4.8 (0.19)	5.5 (0.22)	6.3 (0.25)	6.8 (0.27)
−20%	4.5 (0.18)	5.0 (0.20)	5.8 (0.23)	6.5 (0.26)	6.8 (0.27)
−30%	4.3 (0.17)	4.8 (0.19)	5.7 (0.23)	6.5 (0.26)	6.7 (0.27)

Note: Nugget diameters determined from pulled test coupons, in millimeters (in.) with reproducibility generally better than 0.2 mm (0.01 in.).
* Welds rejected by simple expansion/load monitor systems. (see text).

Discussion

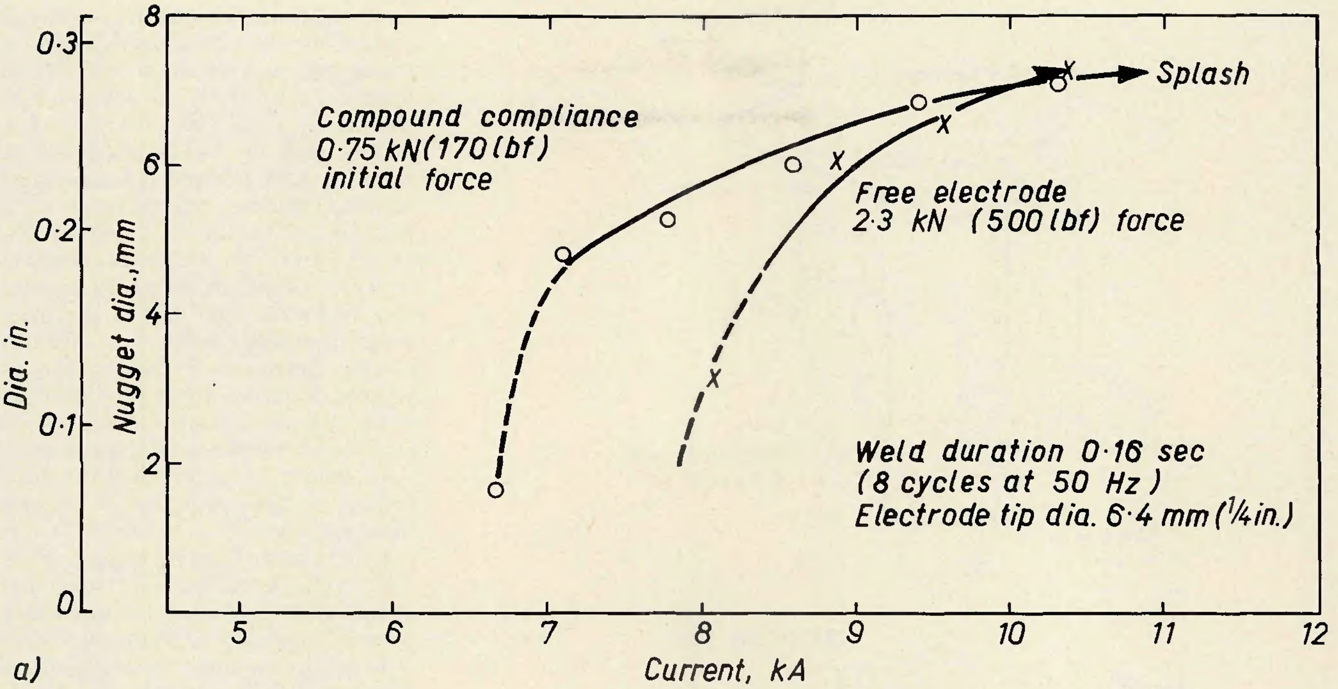
Fixed and Free Electrode Systems

In this context the principal difference in performance with a fixed electrode head and with the normal free electrode is clearly illustrated in Fig. 4 by the tolerance in nugget size to variation in welding current. The effort required to cause the electrode or piston to move back during the welding period is a measure of the degree of restraint occurring. With the free electrode system this is comparatively low (vide the small increase in load during welding current flow shown in the oscillogram Fig. 3a). On the other hand for the locked head tests, the machines used had a rigid frame of low compliance giving a spring rate of over 10 kn/mm (55 lbf/mil) resulting in a considerable increase in load as illustrated in Fig. 3b. This degree of stiffness requires a very positive locking system for the electrode support and in practice the degree of restraint would inevitably be less than that achieved under laboratory conditions.

Nevertheless any methods for jamming or locking the electrodes in place after they have contacted the work will increase (and at worst will not decrease) the tolerance to variations in effective heat input. It is suggested that the minimum amount of restraint to be significantly effective should give at least a 30% increase in load with expansion during the weld cycle. An example of a possible system for locking the moving electrode is shown diagramatically in Fig. 7a where the electrode after an initial squeeze is restrained by the hydraulically operated caliper brake shoe which is operated in conjunction with the weld timer.

Compound Restraint System

The advantage of self-loading of the electrode by expansion is more



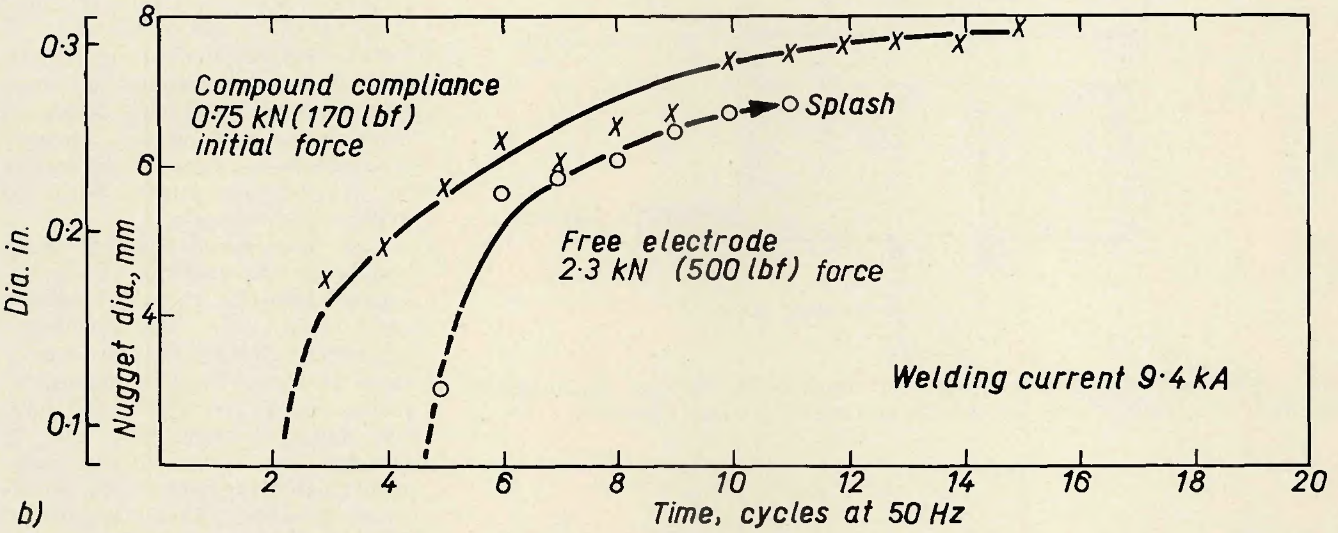


Fig. 6—Nugget growth in 1.6 mm (16 swg) mild steel with free and compound compliance restrained electrode systems: (a) effect of weld current on nugget diameter for constant weld duration; (b) effect of weld time on nugget diameter for constant current

distinctive with the dual or compound spring rate system as evidenced by the results given in Fig. 6a and 6b as well as by the table on performance tolerance. The principal feature in this system is that the initial load is itself low as well as having initially a low spring rate. The design of the electrode support to give initially a sufficiently free movement is simple. For example a small degree of free movement can be provided in the locking system itself or the electrode support can include a thin pad of rubber or other soft material or a flat spring Belleville type washer to give the desired low spring rate.

The higher spring rate is then provided by the complete locking of the electrode or by ensuring that the piston is suitably jammed. One method of preventing free movement of the piston is to use a hydraulic ram in which the fluid circuit is closed during the welding operation. Any reverse movement of the electrode tends then to compress the hydraulic fluid (which has a spring rate of the order of 15 N/mm^2 (2000 psi) for a 1% compression by volume) and hence increases the electrode loading.

The degree of compound compliance can also be readily provided in an all hydraulic system by adding a small freely compressible capsule in the hydraulic circuit. The basic arrangements for an hydraulically actuated electrode are shown diagrammatically in Fig. 7b in which a limited

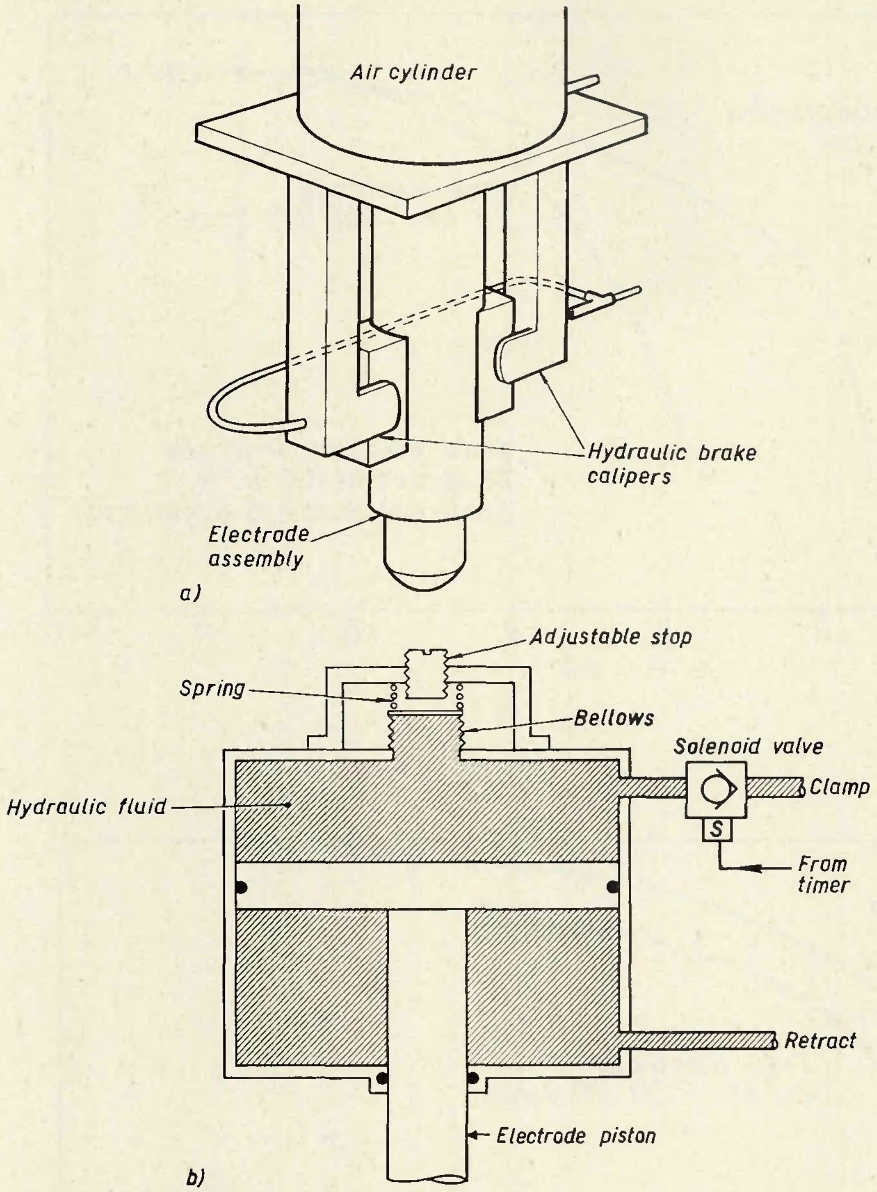


Fig. 7—Schematic diagrams of systems for locked head operation: (a) restrained electrode by external clamp; (b) compound compliance using hydraulic ram

degree of free reverse movement is permitted by the small expansion bellows on the high pressure side of the cylinder. Here the locking is provided by the solenoid valve which is controlled via the weld timer.

With the compound restraint the initial load that is used is low, typically between 25 and 50% of normal levels, so as to encourage nugget development at an early stage in the weld cycle. Weld splash, however, is prevented by the ensuing high spring rate which prevents over-development of the nugget as already described. It is this combination of low initial load and virtually free head together with a high final load, fixed head (as a function of the expansion) which results in the wide tolerance to variations in heat input (welding current) and weld duration, shown by the nugget size data in Fig. 6.

Automatic Weld Quality Monitor

As already discussed, the control of nugget development by electrode load is feasible and it involves a relatively large change of electrode load to be effective. Also the load change is directly caused by the weld expansion. Now it has been established previously that there is a good correlation between head movement (expansion) and weld quality (since the head movement is a direct indication of the nugget development). Hence the expansion measurement can be used as a monitor of weld quality[7] although there is the basic practical difficulty of registering such small movements in industry, particularly on portable machines.

This difficulty is circumvented in the restrained electrode system, since in effect the load change serves as a measure of the head movement obtained. Thus the electrode assembly forms a caliper by which to register the weld expansion and if the electrode actuation point (or effective caliper fulcrum) is locked or restrained from free movement then the stress developed in the locking system corresponds directly with expansion.

It should be noted that the load change is large and can be readily detected especially with the hydraulic type of loading/locking system. Also, since with the locked head with dual compliance the system is essentially tolerant then only a relatively simple weld quality monitor is needed (viz, to detect that the load increased significantly from the low initial level). This corresponds to the formation of the weld nugget which as already described develops early in the weld cycle and then is held from splashing by the increase in electrode load.

Thus for critical weld applications not only does the restrained electrode system provide a greater degree of reliability due to its inherent tolerance to variations in effective weld heating but it provides also a ready means for weld quality assurance.

Tests have shown that this simple monitor of the response of the restrained electrode correctly registers which welds have well established nuggets for a variety of external deviations in the welding conditions, including change of current, weld duration initial electrode load and tip diameter (for truncated cone electrodes) either singly or in any combination. It also registers correctly for shunted welds even in the extreme case of a spot placed between two previous spot welds. The only limitation is that of a weld at the very edge of the sheet which collapses without expansion and expels without increase in load. Here the monitor indicates a suspect weld (pressure failing to increase) even though a nugget was formed before it splashed.

Application of Restrained Electrode Systems

In the work reported a relatively rigid spot welding machine has been used in which the degree of restraint with a locked head is high. This condition applies also to standard bench or fixed station resistance welding machines in which the moving electrode is carried directly by the ram and is not part of an extension arm. The system could also be applied to portable spot welding guns so long as the electrode support arms are relatively short or of such a construction that a reasonably rigid system is achieved. In this connection it is noted that a load change of at least 30% with weld expansion is required.

The restrained electrode system should be applicable to roll spot seam welding but with the addition of some means for compensating for longer term variations such as wheel eccentricity and wear. For this a hydraulically actuated head would be suitable since it could provide both the long term free electrode mechanism and the short term restrained electrode effect. For example, the hydraulic ram could be pressurized by an air cylinder so as to maintain a long term mean load which would allow the system to follow variations in sheet thickness or in wheel radius. However, by providing a constriction in the hydraulic supply, the short term head movement would be restrained and cause a corresponding increase in pressure in the hydraulic fluid which in turn increases the electrode load.

The system should also be applicable to stitch welding but in this case it may not be necessary to incorporate a dual compliance restraint. This arises since there is a stage of negligible head movement or even slight collapse during the initial part of a stitch weld before a positive expansion is registered. This may be due to the overlap of spots whereby the new spot falls on the shoulder or edge of the indentation produced by the previous spot. The detailed mechanism is not known but it is believed that the shoulder initially collapses and offsets the expansion until a nugget is developing at the new point. For the remainder of the weld cycle a positive head movement is registered and with the restrained electrode system this would result in an increasing electrode load to contain the nugget as already described.

For both stitch welding and roll spot seam welding, the weld could also be monitored in terms of the increase in electrode load arising.

Finally it is believed that this new concept in machine design for resistance welding will lead to a greatly increased confidence in this, the oldest, electric welding process for critical applications such as in the aerospace industry and for the structurally important welds in the automobile mass production industry. The increased tolerance in operation and the facility for weld quality assurance has been clearly demonstrated for mild steel sheet and these advantages are expected to apply also to the wide range of materials which are currently resistance welded by the conventional process.

Conclusions

1. Since at a given current and weld duration the electrode load affects the final nugget size, the load can in principle be used to regulate the nugget development and to compensate for variations in effective heat input due (for example) to changes in current. The electrode movement apart (weld expansion) which is an index of the nugget development provides a suitable sensor for control of the load.

2. For weld correction during the weld period, in the simplest arrangement the electrode movement is reacted against a rigid support so that the electrode load increases considerably with expansion according to the stiffness (spring rate) of the support. On a rigid bench welding machine (fitted with stops to prevent movement of the electrode head with respect to the machine frame after the workpiece is clamped) the tolerance to changes in weld current, though limited, is twice that for the normal free system.

3. The restrained electrode system is applicable to many types of resistance welding machine but the maximum spring rate obtainable is limited by the stiffness of the electrode support system especially with portable welding machines.

4. With a compound spring rate (giving initially a low degree of restraint followed by a high stiffness) the weld tolerance is greatly increased over that from a conventional machine with a nominally free electrode head. The nugget diameter for 1.6 mm (16 swg) mild steel is maintained at about 6 ± 1 mm (0.25 ± 0.04 in.) for current variations of +15%, −20% and (at the correct current) for time variations of −50%, +100%. Abnormally low initial electrode loads are used so that the nugget is established early in the weld cycle without splashing but thereafter its further development is inhibited by the dampening effect of the rapidly increasing electrode load.

5. The restrained head provides a means for registering the expansion of the weld by the increased load and hence serves as a monitor of weld quality since, except for a weld at the sheet edge, the nugget formation is closely correlated with expansion. The load monitor reads correctly for variations in current, weld duration, electrode size and for shunted welds. Since the dual compliance system is essentially tolerant, this results in satisfactory welds even with major changes in welding conditions.

6. The combination of the restrained electrode approach with its monitor facility is recommended for weld quality assurance in critical spot welding applications for both the aerospace and mass production industries.

Acknowledgements

The authors express their thanks to the Director General of the Welding Institute for permission to publish this paper and to their colleagues M.D. Hannah and R. G. Newling who were responsible for the experimental data and machine design.

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