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Don Webber [1]

Evaluation of Possible Life Improvement Methods for Aluminum-Zinc-Magnesium Fillet-Welded Details

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ABSTRACT: Fillet welds have a low fatigue resistance compared with other types of weld detail, and it is difficult to design structures without using them. Results are presented of screening tests on methods of life improvement that have been applied successfully to fillet welds in steels under fluctuating tensile loading and are applicable to heat-treatable aluminum alloys. The welding method or shielding gas used did not affect fatigue life: (*a*) improvement of the weld profile during or after welding resulted in slightly increased lives; (*b*) local peening treatments had to be sufficiently intense to produce compressive residual stresses some depth below the surface to cause a worthwhile increase in life; and (*c*) specimen overloading treatments applied both initially and periodically generally were effective but the results for exclusion of the atmosphere by a conventional paint system were inconsistent. Results of tests on as-welded specimens, at various stress ratios which include compression in the loading cycle, corresponded with the results of treatments which include compressive residual stresses. The number of tests of each method was small, and further investigation of the more promising methods is recommended before they can be applied generally without qualifying tests.

KEY WORDS: fatigue tests, weldments, aluminium alloys, fillet welds, fatigue life, life improvement, welding, weld profile, peening, overloading, painting

It is well known that the fatigue strength of a welded structure containing fillet-welded joints in highly stressed regions is low in comparison with the static strength of the parent metal. This is a direct result of the relatively high stress concentration which such joints produce. In general, it is difficult to design structures without using fillet-welded joints and, therefore, it

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[1] Principal scientific officer, Military Vehicles and Engineering Establishment, Christchurch, Dorset, England.

is of considerable value to devise methods of improving fatigue strength of such joints.

Measures often can be taken to improve the fatigue strength of a joint when the determining features have been established. Fatigue failures in welded joints generally occur by crack propagation from external or internal stress concentrations and defects, the most common being from the external stress concentration caused by the welded toe and any defects it may contain. Methods based on the following three principles have been found to produce improvements in fatigue strength for weld toe failures: (*a*) improvement of weld profile, (*b*) modification of the effective stress system by stress relief or preferably the introduction of compressive residual stresses, and (*c*) exclusion of the environment. In addition, it should be possible to improve fatigue strength against failure from internal stress concentrations and defects by using appropriate methods based on the second principle.

It should be noted that the effect of using a local improvement technique may be to change the location of failure, rather than to increase fatigue strength by a significant amount. For instance, a load-carrying weld with an improved weld profile may fail from an internal defect and give approximately the same fatigue strength as the as-welded joint [*1*].[2] A considerable amount of work on methods for improving the fatigue strength of fillet-welded joints in steel structures has been carried out in the past, and much of this work has been reviewed elsewhere [*2*]. However, few comparable tests appear to have been carried out on similar fillet-welded joints in aluminium alloys, and as far as is known no comparable data exist for aluminum-zinc-magnesium (Al-Zn-Mg) alloys. Therefore, the objective of this work was to "screen" a number of possible improvement methods by carrying out fatigue tests on fillet-weld joints for a variety of treatments with a view to define which methods are most likely to be worth further study.

Improvement Methods

Improvement of Weld Profile

A stress concentration results from the change of the cross section at the edge of a fillet weld on a stressed plate and may be expected to have a major influence on the fatigue strength of the joint. The magnitude of the stress concentration depends somewhat on the weld size compared with the plate thickness. However, a more important feature is the shape of the weld profile, a low contact angle resulting in a low stress concentration factor. This is illustrated by the results of experimental and theoretical stress analyses of transverse fillet welds, summarized in Ref *3*, which shows that the stress concentration factor at the weld toe can vary from 1.5 to 4.5 for contact

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

angles varying from 10 to 70 deg. The following methods for improving the weld profile and so reducing the stress concentration have been tried.

Toe Grinding—Many investigations have shown that an improvement with steel can be achieved by machining or grinding the weld to give a gradual transition from weld to plate surface [*2*]. This was repeated in the present investigation using a tungsten carbide burr described as "rounded tree" with an end radius of 1.2 mm rotating at 5 000 to 15 000 rpm. Care was taken to ensure that the grinding marks at the weld end were parallel to the direction of stressing so that additional stress concentrations were not introduced by machining marks. The typical shape of the weld after this treatment is shown in Fig. 1. Grinding had the combined effect of improving poor shapes and removing any sharp inclusions embedded in the weld toe as a result of the weld process. It also exposed porosity, but unlike dressed butt welds this was not observed to be a site for crack initiation.

Gas Tungsten Arc (GTA) Dressing—This method was explored since it has been used with success on steels, welded by other methods, to produce a significant modification to the weld profile and also to remove entrapped inclusions at the weld toe [*4*].

However, postweld treatments of this type are expensive and sometimes difficult to carry out if access to the weld toe is restricted. It would be useful if it were possible to produce welds with good profiles by suitable control during welding.

Welding Method—The gas metal arc (GMA) process is generally used on Al-Zn-Mg alloys, but, in addition, the GTA welding method was used. Also helium shielding gas was used with the GMA method instead of the more usual argon as shown elsewhere [5] for NS8 aluminium alloy (United States equivalent 5083) that it resulted in improved profiles and hence the possibility of improved fatigue life.

Weld Angle—Finally, because of analytical results, results presented by Maddox [*3*], and Christopher and Crabbe's previous experience with steel [*6*], welds were produced having the angles of 15 and 30 deg to the stressed plate in addition to the conventional 45 deg.

Introduction of Compressive Residual Stresses

Three methods of introducing compressive residual stresses are: mechanical working, loading to cause local yielding at stress concentrations, and local heating [*2*]. Mechanical working is useful where it can be applied locally to improve unavoidable details that have a low fatigue strength, but it tends to be expensive if a whole structure requires treatment. Loading, or perhaps more correctly overloading, is attractive because it can be done under controlled conditions and the whole structure is treated in one operation. Overloading has been shown to be particularly effective in improving the fatigue life of mechanical joints [*8*]. Local heating has not been used in view of the sensitivity of the alloy to heat treatment making temperatures above 180°C impractical.

The following methods were used.

1. *Shot Peening*—This method has been shown to be effective on Al-Zn-Mg alloy butt welds [*1*]. Thirty-grade shot was used at an air pressure of 7

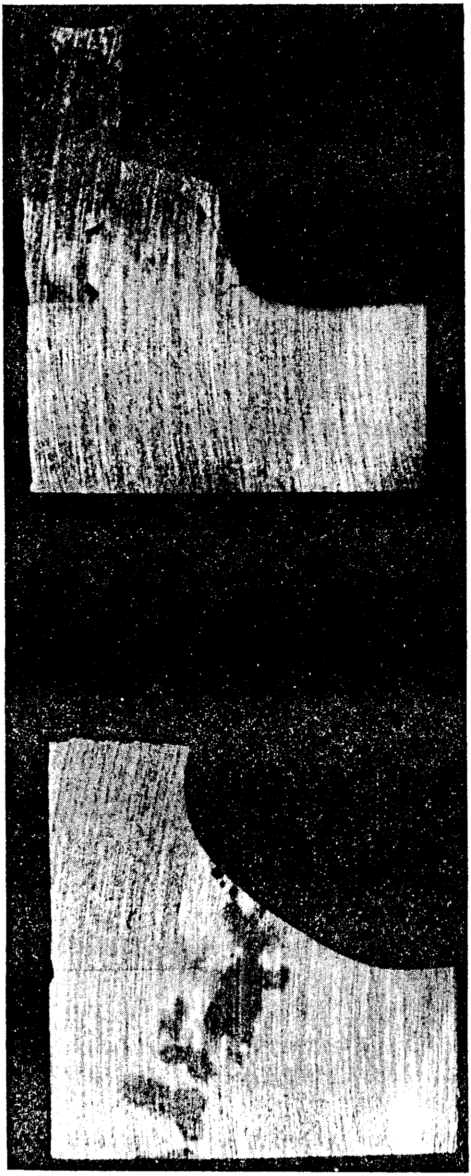


FIG. 1—*Typical weld shapes after local grinding of the weld toe.*

bar with the gun at right angles to the weld surface, and three passes were made to obtain complete coverage.

2. *Hammer Peening*—The efficiency of hammer peening has been demonstrated on steel fillet welds [*6*] and Al-Zn-Mg alloy butt welds [*9*]. It was carried out with a pneumatic hammer fitted with a solid tool which had a round end of approximately 6-mm radius. The piston diameter was 17.5 mm and the air pressure, 7 bar. The gun was traversed approximately 450 mm/min along the weld toes at the ends of the specimen only. This was repeated three times. The finished profile obtained is shown in Fig. 2.

3. *Prior Overloading*—This was carried out by applying either one or 10 "static" stress cycles before fatigue testing. A stress of 277 N/mm^2, applied for 5 s was based on an effective proof stress of the specimen taking account of the reduced strength of the heat affected zone.

4. *Periodic Overloading*—This was expected to reinforce the residual stress field and the stress concentration to give a greater effect than prior overloads. Single or 10 overloads of the same magnitude as the prior overloads were applied at every 1000 cycles. In all cases the tests began with the overload. The interval was chosen to correspond to an annual inspection at the anticipated rate of use of a particular equipment.

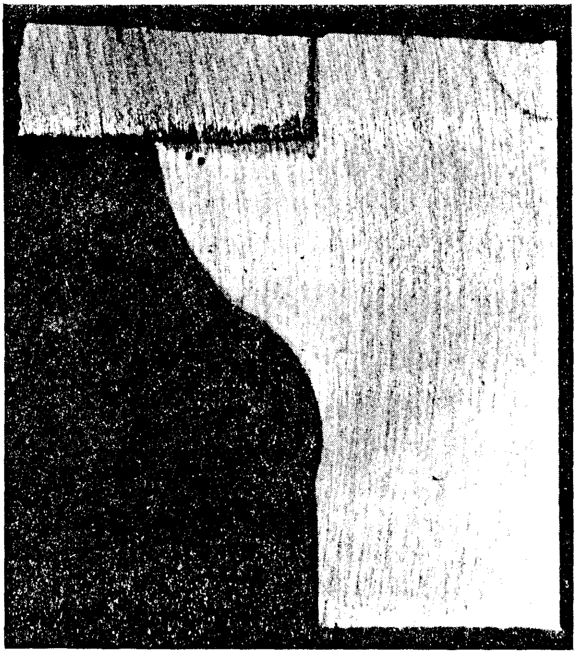


FIG. 2—*Typical weld shape after hammer peening of the weld toe.*

Exclusion of the Environment

Grit Blasting and Painting—In this test series the welds were finished in a way which is used in practice. Usually, fatigue specimens are tested in the as-welded condition and no account is taken of any possible influence of protective finish. The specimens were prepared according to Director General of Fighting Vehicles and Equipment (DGFVE) Specification 235/1, as used for actual Al-Zn-Mg alloy military bridges. This involved grit blasting at 3 bar with nonmetallic alumina grit, zinc spraying to a depth of 0.008 to 0.16 mm, and finally painting with primer, undercoat, and top coat. An improvement in fatigue life as a result of the treatment, of course, could be due to the introduction of compressive residual stresses by grit blasting rather than the exclusion of atmosphere by painting.

Method of Testing

All specimens were subjected to axial load within the frequency range of 5.5 to 11 Hz. In the main axial load fluctuating tension test series the minimum stress was maintained at 31 N/mm^2, and in the majority of cases stress ranges of 154, 92, and 46 N/mm^2 were used. This gave a life range for control specimens from just over 10^4 to beyond 10^6 cycles. However, other stress ranges were used when the treatments were effective and failure had not occurred in 2 x 10^6 cycles at 46 N/mm^2 stress range. The criterion of failure was taken as complete rupture of the specimen. After failure, the weld toe contact angle of the specimens that had not been given improvement treatments was measured and recorded.

In order to verify the effects of introducing compressive residual stresses, a series of zero mean stress ($R = -1$) and fluctuating compressive stress ($R = -\infty$) tests were carried out on untreated specimens. Extensometers were fitted to these specimens to ensure that the loading was truly axial under compressive loads. Failure under fully compressive loading was assumed when the crack had propagated about 25 mm on either side of the center line of the specimens. This condition was detected by cutout wires.

The majority of specimens was tested after a minimum of 15 days natural aging to enable the weld heat affected zone to recover strength; this condition will be described hereafter as as-welded. To investigate the effect of longer periods of natural aging of as-welded specimens in this alloy, some specimens were tested 6 to 7 weeks after welding; this condition will be described hereafter as aged 6 to 7 weeks.

The general form of the specimens used is shown in Fig. 3; it is essentially a 9.5-mm stressed plate with a single longitudinal nonload carrying stiffener or gusset fillet welded to one surface. The material was a weldable Al-Zn-Mg alloy to UK military specification DGFVE 232A, having a chemical composition shown in Table 1, which also shows the range of mechanical properties of the material in the solution and precipitation heat treated (TF) condition in which it was used. A similar United States alloy is 7005.

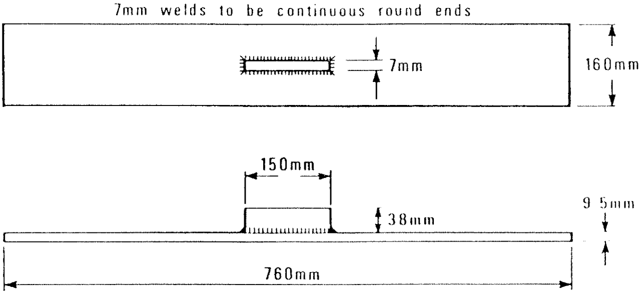


FIG. 3—*Details of nonload carrying fillet-weld specimen.*

This particular specimen type was selected as previous experience had shown the scatter of results to be low compared with those of other specimen types, even though only a small length of the weld is transverse to the stress field. Failure of untreated specimens initiated at the transverse weld toes.

The welds were made in the horizontal-vertical (HV) position with 1.6-mm-diameter NG61 wire (the equivalent United States wire is 5356), with the plate clamped so that the finished specimen was substantially straight. Additional straightening was applied to some specimens. This altered the residual stress level but ensured that consistent stress ranges were applied to the specimens.

The welds around the ends of the stiffener were completed first, and the remainder of the welds were made by welding towards the middle of the stiffener from the ends. This would tend to prevent fatigue cracks initiating from crater cracks in untreated specimens.

The GMA welds were made using the spray transfer technique and 180 A, 20 V direct current with argon flow rate of 14.2 litre/min. GTA welds were made at 250 A, 22 V alternating current and argon flow rate of 7.1 litre/min. Both spray and short arc techniques were used in the case of the helium shielded GMA welds.

A symmetrical double stiffener specimen was found to be necessary so that tests could be conducted wholly in compression in order to investigate the effects of the treatments that produce compressive residual stresses. The specimen was the same as that described with the addition of a second stiffener to the other face.

In view of the known influence of individual welder technique on the fatigue strength of welded joints [7], it was intended that all specimens would be made by the same man. Unfortunately, the original welder left the work and a control group, helium shielded and symmetrical specimens, were made by a different welder.

TABLE 1—*Properties of Al-Zn-Mg alloy to DGFVE specification 232A.*

Chemical composition (nominal)

Element	Al	Zn	Mg	Mn	Zr	Cr	Si	Fe	Ti	Cu
	93.5	4.0	2.0	0.35	0.15	<0.05	<0.2	<0.3	<0.05	<0.1

Mechanical properties

		0.2% Proof Strength, N/mm^2	Ultimate Tensile Strength N/mm^2	Elongation on $5.65\sqrt{S_o}$
From tension tests	range	326 to 380	384 to 437	—
	average	355	411	
From specification (minimum)		332	386	8%

Presentation of Results

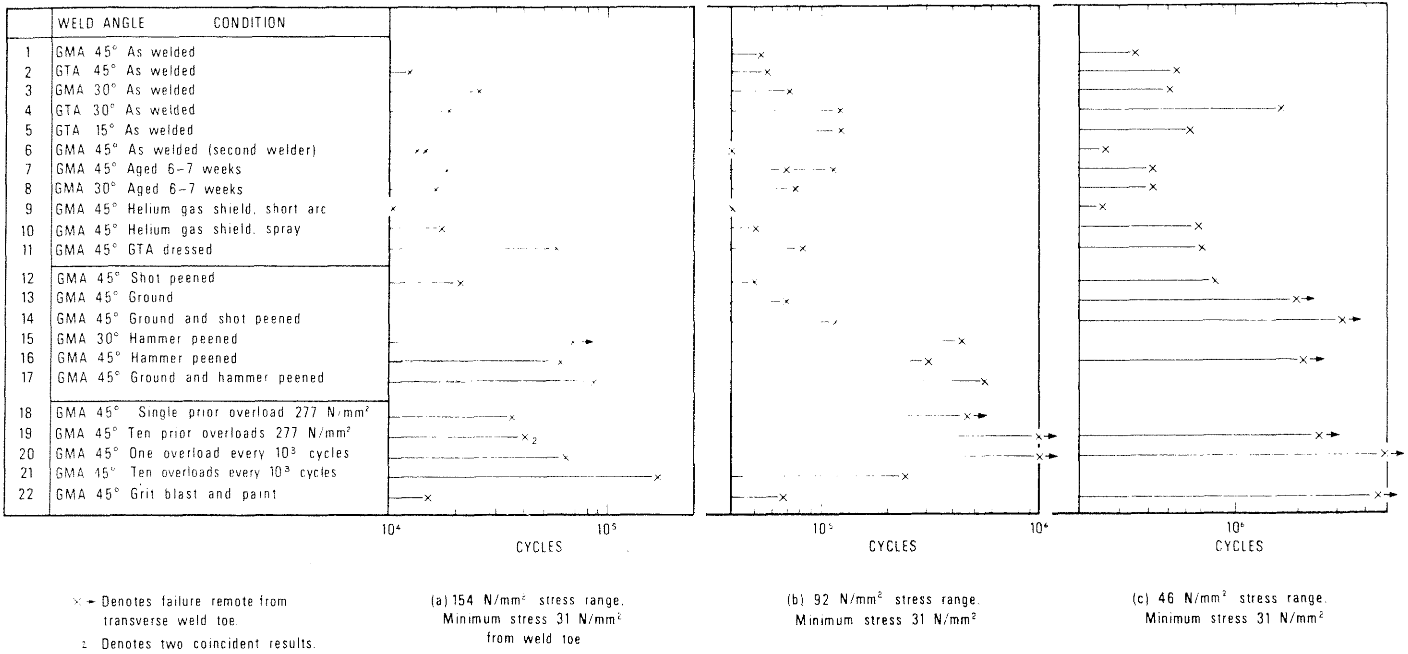
The fluctuating tension results obtained at 154, 92, and 46 N/mm^2 stress ranges have been plotted in Fig. 4(*a*), (*b*), and (*c*), respectively, as bar charts. An analysis was then made of the original GMA and GTA argon shielded welds, ignoring weld angle, and a scatter band embracing these results was plotted on a conventional stress range versus life curve in Fig. 5 together with the remaining results. The measured weld toe angles for untreated welds have been plotted against fatigue life in Fig. 6. Finally, the results at different stress ratios are compared in Fig. 7, with the scatter band just established, and the upper limit obtained for the treatment methods. Comparison of the effectiveness of the treatments investigated has been made on a functional basis of welding variables, postweld treatment applied to the weld toes at the ends of the stiffener, and treatments that affect the whole specimen, in preference to grouping them according to the improvement methods described in the introduction.

Results and Discussion of Tests

Weld Method and Profile

All of the as-welded GMA and GTA specimens prepared by the first welder failed from the weld toe and the results spanned a range of endurances of approximately 3:1 at each stress range. There was a trend for the welds with low specified toe angles to be towards the upper end of the scatter band. However, differences are not considered to be sufficient or consistent enough under the present circumstances to warrant specifying a low toe angle in order to obtain an improved fatigue life. These results have been used to establish a scatter band, shown in Fig. 5, for comparison with the other specimens to which the various treatment methods were applied.

The results for the 45-deg GMA welds from the second welder fell at the lower end of the scatter band as did most of the welds made by the same man with helium shielding gas. Prolonged natural aging for 6 to 7 weeks of the 30 and 45-deg GMA welds also showed no discernible trend compared with as-welded specimens although there was an improvement in the static strength of the specimen. Consistently measured weld toe angles were obtained from the GTA welding process which were close to the specified angle, but there was considerable variation in the GMA welds. They ranged from 27 to 60-deg for 45-deg welds; 25 to 45-deg for 30-deg welds. This confirms the view that there is little likelihood of obtaining consistent improvements in fatigue life by control of weld angles unless GTA or automatic welding can be used. However, in order to estimate the potential of control of weld shape, Fig. 6 was plotted showing weld angle versus fatigue life for each stress range. It is seen that actual weld angle clearly has an effect; research on the control of weld angle therefore would seem to be worthwhile but the potential benefits are small. An examination of helium shielded and argon shielded GMA welds, all of 45-deg specified toe angle, made by the



(a) 154 N/mm² stress range. Minimum stress 31 N/mm² from weld toe

(b) 92 N/mm² stress range. Minimum stress 31 N/mm²

(c) 46 N/mm² stress range. Minimum stress 31 N/mm²

FIG. 4—*The effect of some variables on the fatigue life of nonload carrying fillet weld specimens. Minimum series 31 N/mm² denotes failure remote from transverse weld, 2 denotes number of coincident points. (a) 154 N/mm² stress range. (b) 92 N/mm² stress range.*

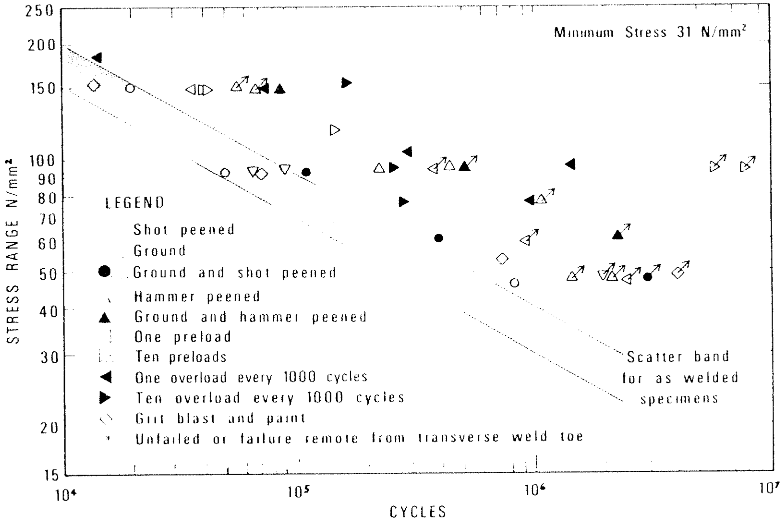


FIG. 5—*The effect of potential life improvement methods on the fatigue life of nonload carrying fillet welds.*

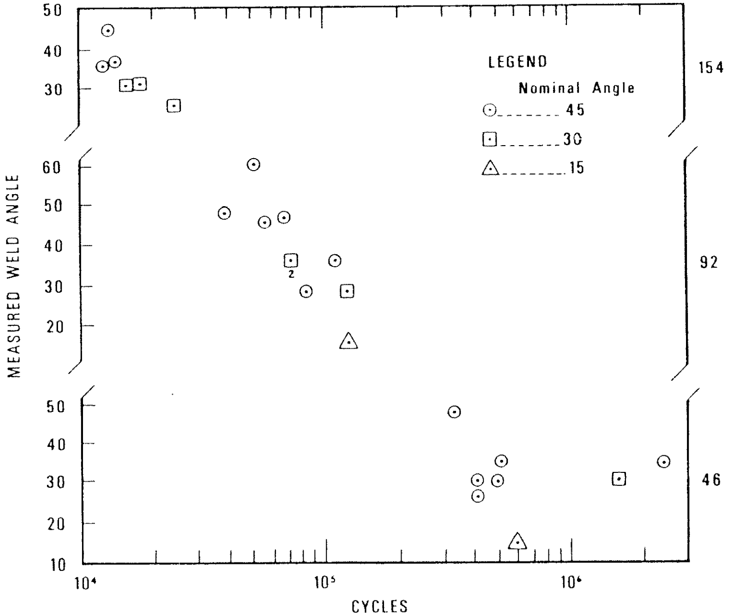


FIG. 6—*The effect of weld angle on the fatigue life of nonload carrying fillet welds.*

second welder, showed that the helium shielded welds made under spray transfer conditions had weld angles of 22 to 30 deg, argon shielded spray transfer welds 37 to 47 deg, while short arc helium shielded welds had toe angles of 40 to 58 deg and a bumpy appearance. There was little scatter except for a low angled helium shielded sprayed transfer weld at 46 N/mm^2 stress range and toe angle of 27 deg, which had a significantly longer life than the upper limit of the scatter band. Although the helium shielded weld showed considerable penetration, this also caused excessive dilution of the welds and the welds were very prone to cracking, so this method of welding had nothing to commend it for welding Al-Zn-Mg alloys.

Microscopic examination of the weld toe of GMA and GTA welds did not reveal sharp nonmetallic defects of the type which caused GMA welds in steel [*4*] to have shorter lives than GTA welds. It appears that both methods of welding result in similar toe conditions and that any inclusions are very small.

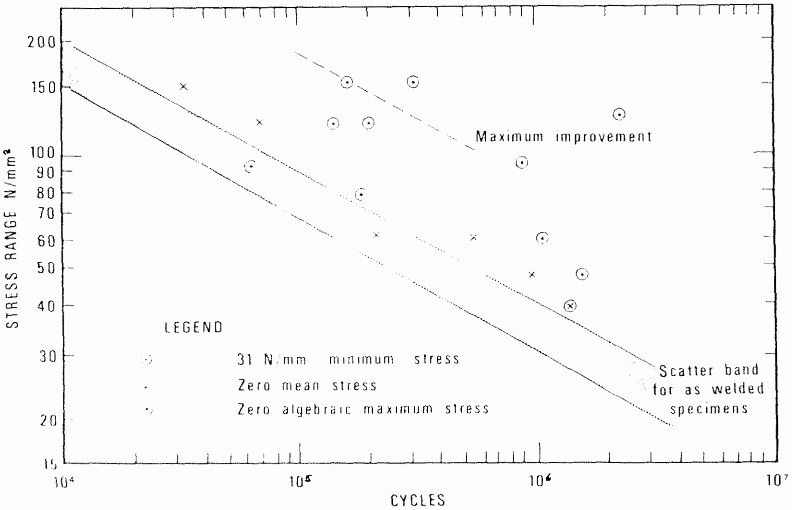


FIG. 7—*The effect of stress ratio on the fatigue life of nonload carrying fillet welds.*

Weld Treatments

GTA dressing of GMA welds was inconclusive except for the specimen tested at 154 N/mm^2 stress range which had a longer life than did any of the welds just presented, the lives for other GTA dressed welds fell within the scatter band. Grinding the weld toe had no effect on life at 92 N/mm^2, but at 46 N/mm^2 stress range the life of one specimen far exceeded the scatter band and eventually broke at the testing machine jaws. Shot peening did not appear to be effective and, not surprisingly, grinding followed by shot peening produced results similar to shot peening alone. Hammer peening, which also resulted in some improvement to weld profile, see Fig. 2, caused at least an eight-fold improvement in fatigue life in comparison with the minimum of the scatter band of results, and the improvement was such that only one out of three failures occurred at the ends of the weld that had been treated. The results of grinding and hammer peening were very similar to hammer peening alone. Figure 8 illustrates a typical failure away from the weld toe.

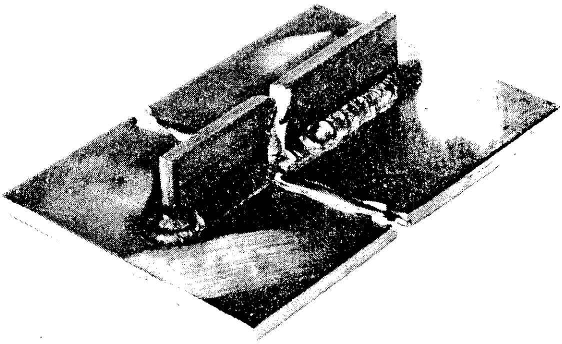


FIG. 8—*Failure of a hammer peened specimen away from the weld toe. Note the subsidiary crack away from the weld toe.*

Specimen Treatments

Grit blasting and painting specimens before testing had no effect on life compared with the scatter band at the higher stress ranges but at 46 N/mm^2 stress range a failure occurred from a weld pore away from the weld end, at a life beyond the limit of the scatter band indicating that there may be some improvement at low stress ranges. A single prior overload causing tensile stress of 277 N/mm^2 in the specimen brought about at least a three-fold increase in life, and at the lower stress ranges failures tended to be at locations other than the weld toe. Ten prior overloads had a similar effect to a single prior overload for a test at 154 N/mm^2 stress range, but at lower stress ranges the beneficial effect was much greater and exceeded that for hammer peening. When the overloads were repeated at intervals of 1000 cycles they also showed an improvement, the ten overloads being the most effective improvement method at 154 N/mm^2 stress range, but at lower fatigue stress ranges a single overload seemed to be more advantageous. As the fatigue stress range was reduced and the total number of overload cycles increased, the improvement became less than for prior overloads. The overload stress which was selected initially for the GMA welded specimen was so high that it was not possible to overload GTA welded specimens to the same level and they broke in the reduced strength region of the heat affected zone, which is more extensive than for GMA welds.

The effect of periodic overloading depends on the magnitude, number, and interval of applications of overload stress. At low test stress ranges the very process of periodic multiple overloading is fatigue damaging and will eventually limit the fatigue life. Alternatively, had a lower overload stress been used, the benefit due to the introduction of local compressive residual stresses would have been less, but the maximum possible endurance at lower test stress ranges might have been greater. If the interval between overloads had been greater so that the total number of overload cycles had been less, the beneficial effect of each overload cycle would have been similar, and it is again possible that the endurance would have been greater. The optimum condition, which would introduce greater benefit than the application of prior overloads only, would be the application of overloads when the retardation in crack growth due to the previous loads had disappeared. Such conditions would probably have to be derived by carrying out fatigue crack propagation tests and would only be appropriate to a particular type of operating conditions.

Prior overloading ten times is clearly the best general method of specimen treatment, but it would not be practical to use such high prior overloads on structures because of dimensional tolerance requirements and variations in material properties, and consequently the magnitude of improvement shown in these experiments could not be expected to be attained.

Stress Ratio

The zero mean stress results ($R = -1$) fell just above the upper end of the scatter band with the wholly compressive tests ($R = -\infty$) generally beyond these, Fig. 7, but exhibited large scatter in life and location of failure, most being from weld ripples and crater cracks away from the toes at the weld ends.

Measured residual stresses in parent plate at the weld toe ranged from 178 N/mm^2 tension to 157 N/mm^2 compression. The stresses tended to be lower for the specimens with the double gusset used for the stress ratio experiments and the greatest tensile stresses were in the direction of loading. Failure under cyclic compressive loading depends on the residual stresses causing an effective tensile stress range. Residual stresses are likely to be larger in structures than in specimens because of the bulk of the material and the remoteness of welds from free edges, so the lives would be lower than the present specimen lives suggest. It has been noted [*9*] that the weld would contain a much higher residual stress than exists in the heat affected zone at the toe of the weld, so although the nominal stress range would be lower in the section containing the weld than at the toe, due to the increased cross-sectional area, it is possible for it still to be wholly tensile, whereas at the toe the tensile portion of the stress range would be limited to the value of the tensile residual stress. This could account for the large amount of scatter of life and location of failure at surface ripples, crater cracks, and buried defects which would normally be harmless compared with the weld toe. At lives of less than the 10^6 cycles, Fig. 7 also shows that the results for compressive applied loads are consistent with the life improvement methods that involved treatments causing compressive residual stresses.

General

After the fatigue tests were completed, residual stress measurements were made in the toe of the welds of similar details. Grit blasting caused a peak compressive stress of at least 300 N/mm^2 at 0.25 mm below the surface which then reduced rapidly. Hammer peening caused a peak stress of 240 N/mm^2 at 0.6 mm below the surface which had only fallen to 75 percent of this value at 1.2 mm. The results for shot peening were similar to grit blasting but the depth extended to about 0.5 mm. The results indicate that any peening method must produce an adequate depth of sufficiently high residual compressive stress to be effective and further work is necessary to define the conditions under which this is so. Corresponding residual stress measurements are not available for the overloading specimens, but from the fatigue results they appear to be similar to hammer peening. The results for toe grinding were disappointing compared with the results for measured weld angle; as seen in Fig. 2, conditions at the weld toe were improved but there was still a rapid change in section sometimes and the reduction in stress concentration would not be as large as indicated by the toe angle. Unlike the case with steels, the method does not appear to be cost effective when applied to aluminium alloy fillet welds.

Concluding Remarks

Within the limited range of the present investigation under tensile loading, the following results of potential methods of increasing fatigue life were apparent.

1. The welding method (GMA and GTA) does not have a significant effect on life.
2. Decreasing weld angle caused a small increase in life, but the weld angle is not easily controlled, particularly with GMA welds.
3. The shielding gas (argon or helium) does not appear to have a significant effect on life, but helium shielding gas is not satisfactory on account of weld cracking.
4. Grinding weld toes does not appear to be effective at high stress ranges, but may be beneficial at low stress ranges if the whole weld profile is improved.
5. Light shot peening or grit blasting does not improve fatigue life, but a more severe hammer peening was effective, a certain depth of relatively high compressive residual stress appears to be necessary to obtain an improvement in fatigue life.
6. Combined grinding and peening was no more effective than peening alone.
7. Prior overloading was effective; the improvement was not as great as

with hammer peening at high stress ranges, but became more effective at the lower stress ranges. Ten prior overloads were better than one at low stress ranges.

8. Periodic overloading improved life at high stress ranges, but the effect was not so great at lower stress ranges.

There was little that could be done during welding to produce a substantial improvement in fatigue life, but weld treatments and specimen treatments that induced compressive residual stress fields of sufficient magnitude were extremely effective. There is little to choose between severe peening and 10 prior overloads in effectiveness and the choice depends on individual circumstances. The control of treatment clearly needs some care and the comparison had not been extended beyond the constant amplitude loading.

Acknowledgments

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