Improving the fatigue strength of fillet welded joints by grinding and peening

J.W. Knight

1. INTRODUCTION

Welded structures subjected to cyclic loading can become unserviceable due to fatigue cracks propagating from the toe region of fillet welds. For such structures it is not possible to take advantage of the improved mechanical properties of high strength steel, unless the upper limits of the cyclic service stresses can be greater than the design stress of the low carbon steels commonly used in structural fabrication. This may be possible either under low cycle fatigue conditions or with certain types of load spectra having a few cycles of high stress.

Considerable work has been carried out in the past (2, 3, 4 and 6) to show that various techniques, such as grinding, peening, spot heating and TIG dressing, can all improve the fatigue strength of welded joints, and some attempt has been made (5) to compare the costs of applying such techniques.

The objective of the work described in this report is to investigate further the benefits which can be gained from the use of weld grinding and peening, for specimens fabricated from both BS 4360 Grade 43A (245N/mm^2 yield strength) and Superelso 70 (685N/mm^2 yield strength) steels. The programme is an extension to earlier work (1) which compared various grinding techniques, and emphasis is placed on both the economics and practical application associated with fabrication site conditions.

2. PREVIOUS WORK

It has long been established that techniques such as grinding and peening can improve the fatigue strength of welded joints. Gurney (2) showed that grinding fillet welds in transverse non-load-carrying joints to a high quality finish gave a 100% improvement in fatigue strength at 2 x 10^6 cycles. Alternatively, light grinding of the weld toe still gave fatigue strength improvements between 60 and 85% compared with specimens in the as-welded condition. The results for three peening techniques are given by Gurney, namely shot peening, multiple wire hammer peening and solid tool hammer peening, for which the improvement in fatigue strength at 2 x 10^6 cycles compared with as-welded specimens is given as 39%, 52% and 91% respectively. The general trend emerging from the results quoted by Gurney revealed that, whereas grinding gave considerable improvements in fatigue strength for all cyclic stress levels investigated, the beneficial effect of peening was evident in the low stress-long life tests, but became much less significant as the stress range approached the material yield stress. Tests by Watkinson, et al. (3) on transverse non-load-carrying fillet welded specimens fabricated from a low carbon multi-alloy quenched and tempered steel (725N/mm^2 yield strength), revealed a tendency for the S-N curves for both ground and peened specimens to diverge as life is increased. A similar tendency was noted by Harrison (4) for tests on welded joints made from steel to the same specification.

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A cost comparison is quoted in Ref. 5, in which the ratio between the costs of 2-pass peening and deep grinding is given as 1:110. Deep grinding consisted of removing the sharp defects, such as slag inclusions, which could be sited at the bottom of the toe undercut. Such defects can have a maximum depth of approximately 200µm and it is suggested by Watkinson (3) that once the weld toe is ground sufficiently to remove the undercut, an additional 500µm should be ground out in order to be certain of removing all sharp defects. The above cost estimate included time for measuring the grinding depth and, if this is ignored, the cost ratio between 4-pass peening and deep grinding, based on Harrison's approach, is nearer 1 : 40.

3. TEST PROGRAMME

In order to establish datum curves for the as-welded condition nine specimens fabricated from BS 4360 Grade 43A plate and five using high strength steel have been tested. Data relating to the various grinding techniques described in this report were obtained by testing a total of twenty-seven specimens using Grade 43A material and eleven specimens fabricated from high strength steel. The results of the peening technique were obtained from twenty-three Grade 43A specimens and four high strength steel specimens.

4. TEST SPECIMENS

4.1. Manufacture

All tests were carried out using the transverse non-load-carrying fillet welded specimens as illustrated in Fig. 1. The transverse gussets were made shorter than the plate width so that the fillet welds did not cause undercutting of the plate edge. Each fillet weld was made in two halves by starting at the ends of the gusset and finishing on the plate lateral centre-line. These two precautionary measures ensured that cracks did not occur either at the plate edge or at weld end craters.

The fabrication of all specimens was carried out by the same welder with the weld in the flat position. Rutile electrodes to BS 1719 : 1969 Class E3XX were used to weld the BS 4360 Grade 43A specimens and Class E6XX basic electrodes were used for the high strength steel specimens.

The chemical composition and mechanical properties of the two materials of fabrication are given in Table 1. Three different plates were used for the BS 4360 Grade 43A specimens.

4.2. Grinding

The objective of toe grinding is to remove the undercut and defects at the weld toe on the stressed plate, giving a smooth transition between the weld metal and the plate. For the heavy disc grinding technique, as illustrated in Fig. 3, it has been shown (1) that, if the angle between the disc and the plate is approximately 30°, metal can be removed at a reasonable rate and still results in a smooth blend profile at the weld toe. One problem with the heavy disc grinding technique is that the score marks resulting from grinding are perpendicular to the direction of applied stress and it has been shown (2) that fatigue cracks tend to follow the line of score marks if they are inclined to the direction of applied stress. A specimen profile after heavy disc grinding is illustrated in Fig. 4. The grinding discs used for the series of tests described in this report were 100mm (4in) diameter with a 36 grit in an epoxy matrix.

Two grinding techniques using a burr grinder were investigated and are referred to as toe burr grinding and full burr grinding in this report. Toe burr grinding is achieved by grinding the weld toe with the burr tools illustrated in Fig. 5, and this technique effectively removes the undercut and defects which occur at the weld toe region. Full burr grinding employs the burr tools over the complete weld profile followed by treatment with the grinding bands shown in Fig. 5. For both these techniques the surface score marks are parallel with the direction of applied stress and the surface appearance is more highly polished for full burr grinding compared with heavy disc grinding and toe burr grinding.

The average depth of grinding at the weld toe, as defined by Fig. 2, was approximately 0.8mm for heavy disc grinding, 0.4mm for toe burr grinding and 0.5mm for full burr grinding.

4.3. Peening

The objective of peening the weld toe region is to introduce compressive residual stresses at the usual initiation area for fatigue cracks. The appearance of the weld toe after peening is illustrated in Fig. 6, together with a 6.4mm (0.25in) tip radius spherical hammer bit. Since the hammer tends to jump and miss small regions, a single pass along the weld toe is not usually sufficient to ensure that no area remains in the as-welded condition after peening. Consequently, the effect of different numbers of passes of the peening tool has been investigated. Specimen profiles after peening are illustrated in Fig. 7 and Fig. 8.

5. TEST METHOD

All tests were carried out under axial, constant amplitude loading with the stress ratio $R = \sigma_{min}/\sigma_{max} = 0$. The testing machine was a Losenhausen 400kN machine with a testing speed of either 333, 500 or 666 cycles per min.

The failure criterion was defined as complete separation of the specimen and testing was designed to produce S-N curves in the range 2×10^4 to 10^7 cycles. Consequently, no test was continued beyond 1.2×10^7 cycles and all the unbroken specimens at the end of fatigue testing were broken open to see whether cracks had initiated; in fact none were found.

6. COMPARATIVE COSTS

In an attempt to investigate the comparative costs of the four improvement techniques studied in this report an approximate estimate of the man-hours involved and cost of grinding discs, bands and burrs, is given below.

Technique	Man-hours per metre length of weld	Consumable cost per metre length of weld, £
Heavy disc grinding	0.5	0.2
Toe burr grinding	0.9	0.3
Full burr grinding	3.0	1.0
4-pass peening	0.25	0

The estimates are based on work carried out by laboratory technicians on 10mm fillet welds and can only be taken as a rough guide to actual costs under site conditions.

Assuming that the consumable costs are negligible with respect to labour costs, and taking the cost of the 4-pass peening technique as unity, the following comparison can be made.

Technique	Approximate comparative cost
4-pass peening	1
Heavy disc grinding	2
Toe burr grinding	3 to 4
Full burr grinding	12

7. RESULTS AND DISCUSSION

7.1. Grinding

Test results for specimens fabricated from BS 4360 Grade 43A are given in Fig. 10 and the results for the high strength steel specimens are given in Fig. 11. To each set of results the best curve fit has been drawn and these are reproduced for all tests in Fig. 12. It will be seen that in general the degree of improvement of fatigue performance increases in the order of heavy disc grinding, toe burr grinding, full burr grinding and 4-pass hammer peening, although heavy disc grinding does in fact give a greater improvement than toe burr grinding for Grade 43A material in the low stress-long life range.

Comparing the curves for specimens in the as-welded condition it will be seen that there is no advantage in using the higher strength material under conditions represented by the low stress-long life range in Fig. 12. Since the crack initiation period in the life of a welded specimen subjected to fatigue loading is usually very small, the life of the specimen can be considered as the time taken for the crack to propagate to a critical length. For steel specimens where the crack initiates at a weld toe and subsequently propagates through the plate, the rate of crack propagation, and consequently the life of the specimen, will be approximately independent of the material strength. Hence, there is no advantage in using high strength steel for as-welded steel specimens under fatigue loading unless the upper limit of the cyclic stress level exceeds the static design stress of the lower strength material.

Grinding the weld toe region will remove undercut and defects from the region where cracks often initiate. In addition, the change in geometry is less abrupt after grinding and a smooth transition between the weld metal and the plate will reduce the stress concentration effect at the toe. The first of these effects is to introduce a crack initiation phase into the specimen life and the second effect will reduce the cyclic stress range applied to the weld toe region.

From Fig. 12 it is evident that the improvements in fatigue strength due to grinding can be considerable and that specimens made from the higher strength material will benefit more than those fabricated from Grade 43A material if the same grinding technique is used. This point is illustrated quantitatively by Tables 2 and 3 which compare fatigue strength and endurance values respectively. As typical examples the improvements in fatigue strength at 2×10^5 cycles for heavy disc grinding, toe burr grinding, full burr grinding and 4-pass hammer peening compared with the as-welded condition are 7, 20, 30 and 36% respectively for BS 4360 Grade 43A specimens and 36, 64, 85 and 105% respectively for the high strength steel. Alternatively, the improvements in fatigue life for a stress range of 220N/mm^2 for heavy disc grinding, toe burr grinding, full burr grinding and 4-pass hammer peening compared with the as-welded condition are 35, 120, 400 and 1400% respectively for BS 4360 Grade 43A specimens and 193, 1900, unknown and 3900% respectively for the high strength steel.

From these results it is evident that, of the three grinding techniques studied in this investigation, full burr grinding gives the greatest improvement in fatigue strength. However, the cost of the full burr grinding operation is approximately three to four times that of toe burr grinding and six times that of heavy disc grinding. For the two cheaper grinding techniques it would appear that toe burr grinding is superior for the high strength steel with little to choose between them for the Grade 43A material. It should, however, be noted (Fig. 10) that the S-N curves for both these cheaper grinding techniques show evidence of a knee at about 150N/mm^2 stress range. This is close to the permissible static design stress for mild steel and suggests that either technique could be used to advantage.

The intersection of the S-N curves close to the material yield stress for the as-welded and ground specimens originally suggested that residual stresses may be induced due to the grinding action. Consequently, five specimens were stress relieved after grinding and the test results are given in Fig. 13. The results for the stress relieved specimens approximately follow the curve for specimens tested without stress relieving and there is no evidence of a residual stress effect being responsible for convergence of the S-N curves. It therefore seems probable that the change in slope of the S-N curve for the ground specimens is due to the introduction of a crack initiation period which is relatively longer at low stresses than at high stresses.

7.2. Peening

The results of the tests on peened specimens fabricated from BS 4360 Grade 43A plate are given in Fig. 14 with a typical fracture illustrated in Fig. 9. The improvement in fatigue performance is dependent on the number of passes, as will be seen from both Fig. 14 and Table 4. The peening process produces residual compressive stresses in the region where fatigue cracks occur, namely at the weld toe. Consequently, the tensile component of the cyclic stress range is reduced, which will result in a reduction in crack propagation rates. In general the curves of Fig. 14 tend to diverge with increased life and the values of inverse slope for the as-welded and 1, 2, 3 and 4-pass peened specimens are 3.50, 4.65, 4.10, 7.63 and 8.47 respectively. This divergence results in greater improvement in performance in the low stress-long life range. For example (see Table 4), the improvements in fatigue strength at 2×10^5 cycles for 1, 2, 3 and 4-pass peening are 4, 30, 15 and 22% respectively whereas the improvements at 2×10^6 cycles are 30, 43, 74 and 91% respectively.

One specimen was peened with six passes of the hammer and another was treated with eight passes. The resultant improvement in performance of these two specimens was not appreciable compared with 4-pass peened specimens. Consequently, it is thought that 4-pass peening involves the maximum necessary operation time for a reasonable improvement in fatigue performance.

It should be noted, however, that the tests were carried out under constant amplitude loading and, since the benefits of peening result from the introduction of compressive residual stresses, the improvement might not be so great under variable amplitude service loading conditions in which high periodic tensile stresses might relieve the beneficial effect of the residual stress distribution.

7.3. Quantifying the degree of peening

An attempt to quantify the peening technique was made by peening the surface of a piece of BS 4360 Grade 43A plate. The depth of peening was measured with a dial gauge after each pass of the peening tool and the results are illustrated graphically in Fig. 15.

In order to standardise the peening operation and take account of the variation in both hammer performance and operator technique, it would be possible to specify a peening depth on the trial piece of parent plate before weld toe peening commenced on the real structure. For example, the equivalent to 4-pass peening could be specified as a peening depth of 0.6 ± 0.1mm, and the number of passes required to achieve this on the plate sample would then be used for welds on the real structure.

CONCLUSIONS

Fatigue strength improvement techniques have been investigated for transverse non-load-carrying fillet welded specimens fabricated from both BS 4360 Grade 43A steel ($245 N/mm^2$ yield strength) and high strength steel ($685 N/mm^2$ yield strength) plate. Three weld grinding techniques and the influence of peening have been studied. The results of the investigation can best be stated as follows:

1. All the techniques gave improvements in fatigue strength compared with the as-welded condition, for both types of material. In general, the degree of improvement in fatigue performance increased in the order of heavy disc grinding, toe burr grinding, full burr grinding and 4-pass hammer peening, although heavy disc grinding was superior to toe burr grinding for Grade 43A material in the low stress-long life range. However, for heavy disc grinding and toe burr grinding there is evidence of a knee in the S-N curve at about $150 N/mm^2$ stress range. This is close to the permissible static design stress for mild steel and suggests that either of these two cheaper grinding techniques could be used to advantage.
2. The percentage increase in fatigue strength due to a particular improvement technique was in general greater for the high strength steel specimens than for specimens fabricated from Grade 43A material. For example, the improvements in fatigue strength at 2×10^5 cycles for heavy disc grinding, toe burr grinding, full burr grinding and 4-pass hammer peening compared with the as-welded condition are 7, 20, 30 and

36% respectively for BS 4360 Grade 43A specimens and 36, 64, 85 and 105% respectively for the high strength steel.

3. Compared with the as-welded condition the S-N curves for all improvement techniques diverge with increasing life. Consequently, the greatest improvement in fatigue performance occurs in the low stress-long life range. For the peened specimens, the degree of divergence increases with the number of passes of the peening tool.
4. For the peened specimens the improvement in fatigue performance increased with the number of passes of the peening hammer, but it is thought that 4-pass peening is the optimum with respect to improved performance and operator time.
5. In order to standardise the peening operation and take account of the variation in both hammer performance and operator technique it is suggested that the degree of peening can be defined by the depth of indentation.
6. An approximate guide to actual costs under site conditions suggests that the ratios of costs for a given length of weld, for 4-pass peening, heavy disc grinding, toe burr grinding and full burr grinding are 1:2:3:12 respectively. Thus the technique which appears to be most attractive commercially is 4-pass hammer peening.

ACKNOWLEDGEMENT

Much of the work reported here was supervised by K.G. Schofield before leaving The Welding Institute and the author is indebted to him for the clarity of his records. The author would also like to thank the staff of the fatigue laboratory for the efficiency with which the experimental work has been carried out.

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TABLE 1. Chemical composition and specified mechanical properties of specimen materials

Material specification	Plate no.	Chemical composition, %						Yield stress (min) N/mm^2	Tensile strength, N/mm^2
		C	Si	S	P	Mn	Cr		
BS 4360 Grade 43A	1	0.16	-	0.013	0.016	0.78	-	245	430/510
	2	0.11	0.27	0.015	0.031	0.55	-		
	3	0.24	-	0.034	0.034	0.28	-		
Superelso 70		0.19	-	0.020	0.014	1.46	0.82	685	785/930

TABLE 2. Comparison between fatigue strength values for improvement techniques

Improvement technique	N = 2 x 10^5 cycles		N = 10^6 cycles		N = 2 x 10^6 cycles	
	BS 4360 Grade 43A	Superelso 70	BS 4360 Grade 43A	Superelso 70	BS 4360 Grade 43A	Superelso 70
As-welded	220	195	140	105	110	-
Heavy disc grinding	235	265	175	180	165	-
Toe burr grinding	265	320	180	240	155	225
Full burr grinding	285	360	220	270	200	-
4-pass hammer peening	300	400	250	300	230	265

All stress values in N/mm^2

TABLE 3. Comparison between specimen endurance values for various improvement techniques

Improvement technique	Stress range = 220N/mm^2		Stress range = 280N/mm^2	
	BS 4360 Grade 43A	Superelso 70	BS 4360 Grade 43A	Superelso 70
As-welded	2.0	1.5	-	0.8
Heavy disc grinding	2.7	4.4	0.8	1.6
Toe burr grinding	4.4	30.0	-	3.1
Full burr grinding	10.0	-	2.2	8.0
4-pass hammer peening	30.0	60.0	3.5	15.0

All endurances in cycles x 10^5

TABLE 4. Comparison between fatigue strength values for peened specimens

Number of passes	$N = 2 \times 10^5$ cycles	$N = 2 \times 10^6$ cycles
As-welded	230	115
1	240	150
2	300	165
3	265	200
4	280	220

All stress values in N/mm^2

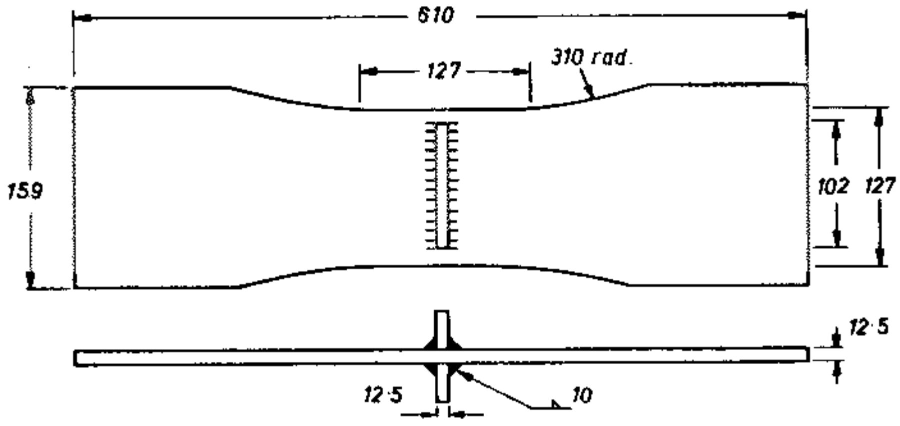

Fig.1. Test specimen configuration.

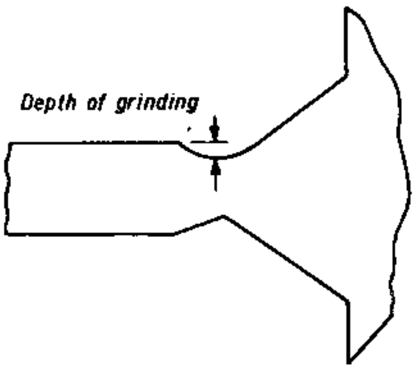

Fig.2. Definition of grinding depth.

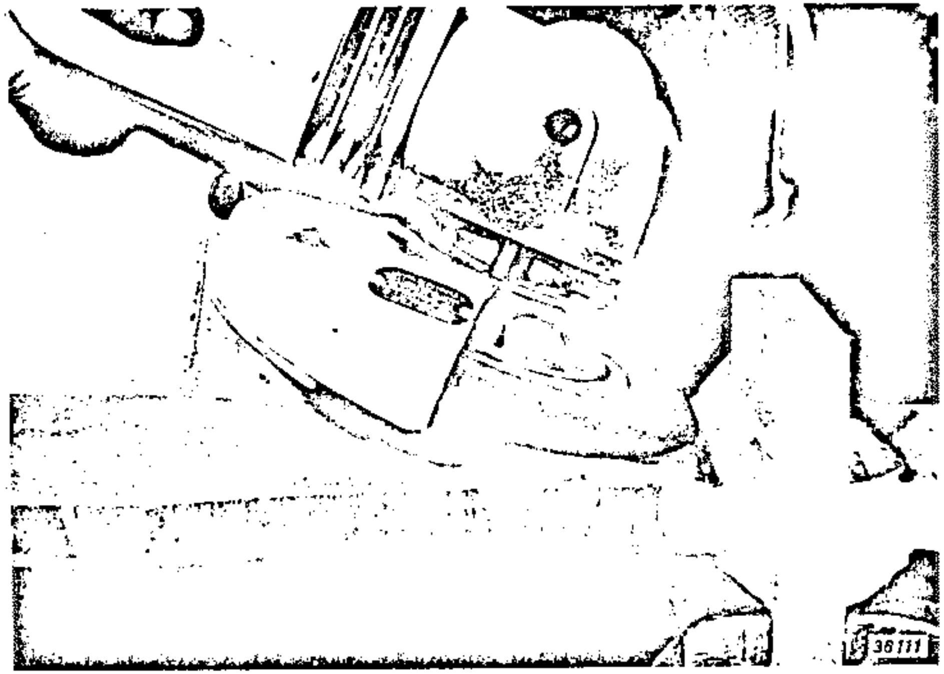

Fig.3. The disc grinding operation.

Fig.3. The disc grinding operation.

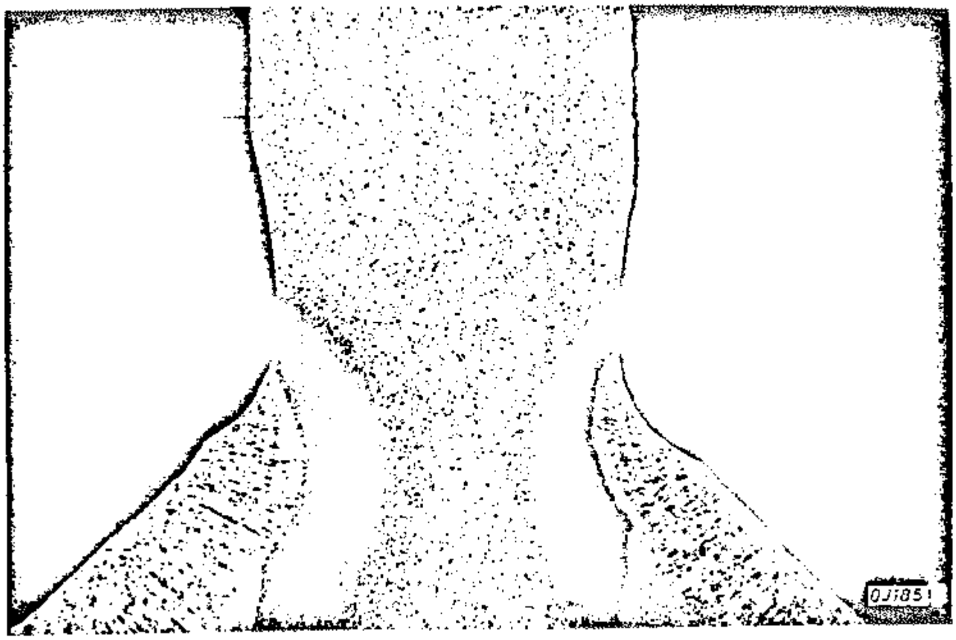

Fig.4. Specimen profile after heavy disc grinding.

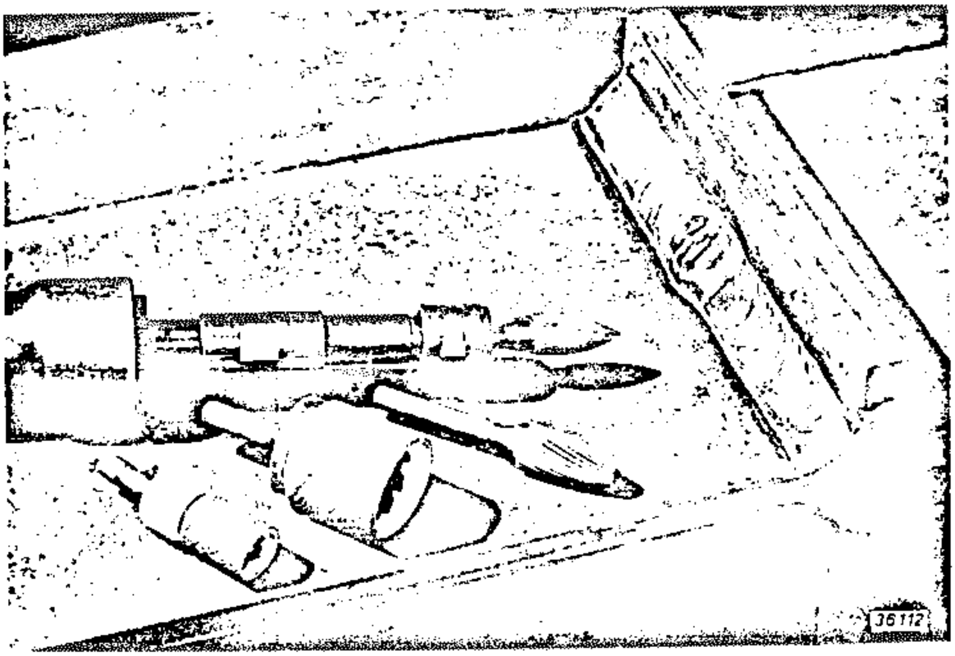

Fig.5. Appearance of specimen after toe burr grinding showing the tools used for the two burr grinding techniques.

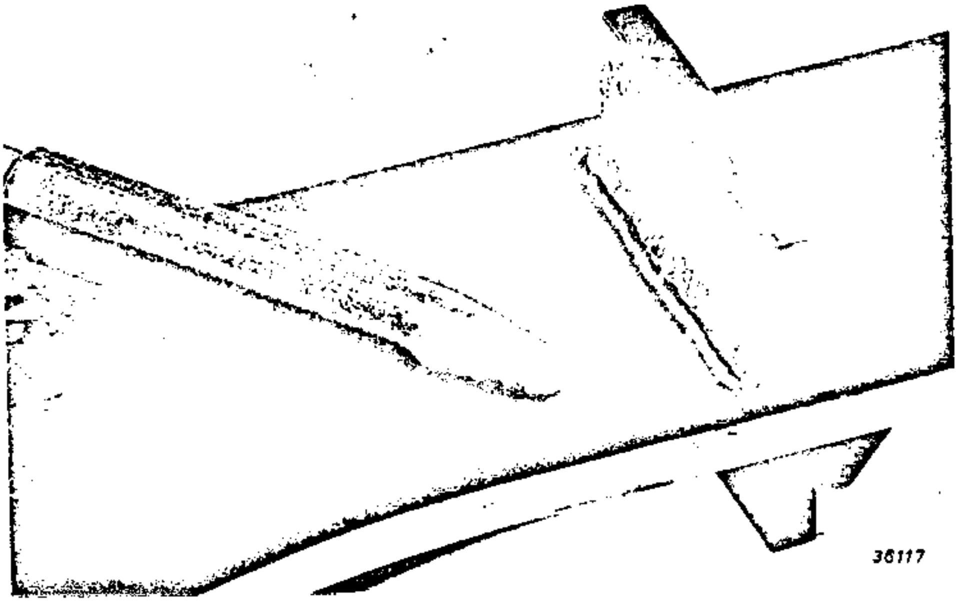

Fig.6. Appearance of peened specimen showing the spherical hammer bit (3 pass peening illustrated).

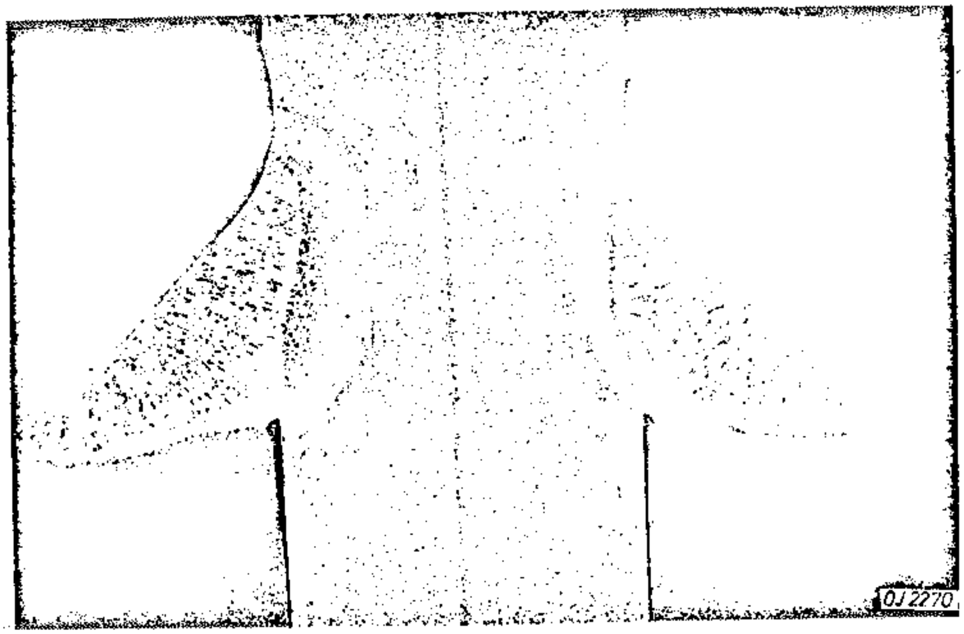

Fig.7. 2-pass peening.

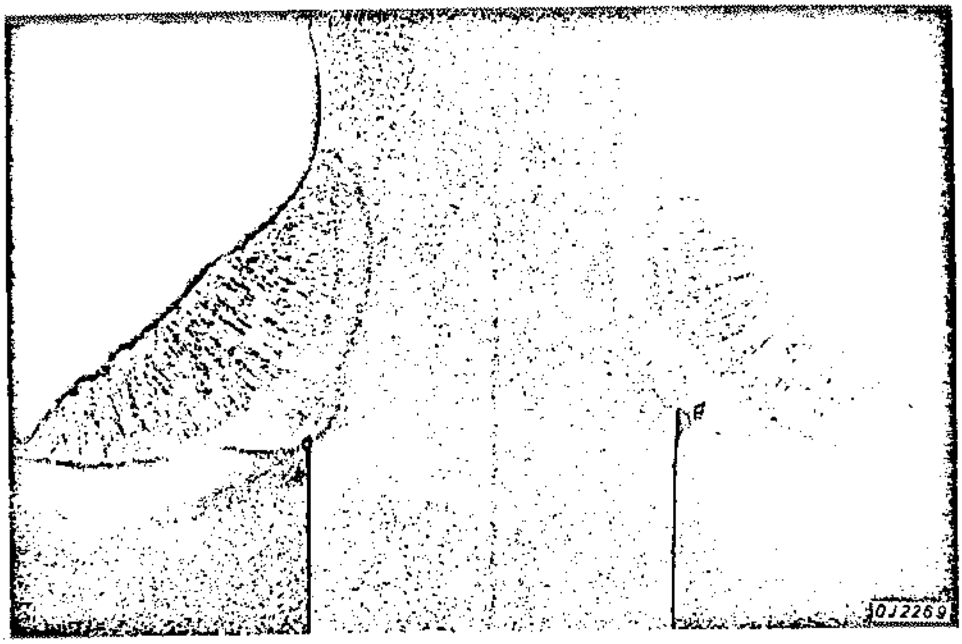

Fig.8. 4-pass peening.

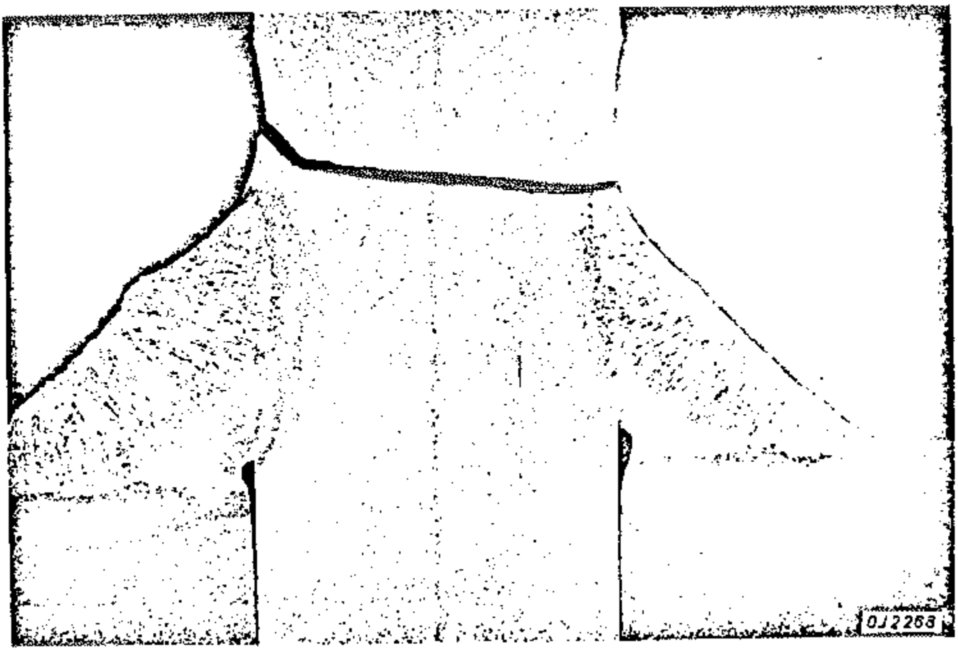

Fig.9. 4-pass peening specimen fracture.

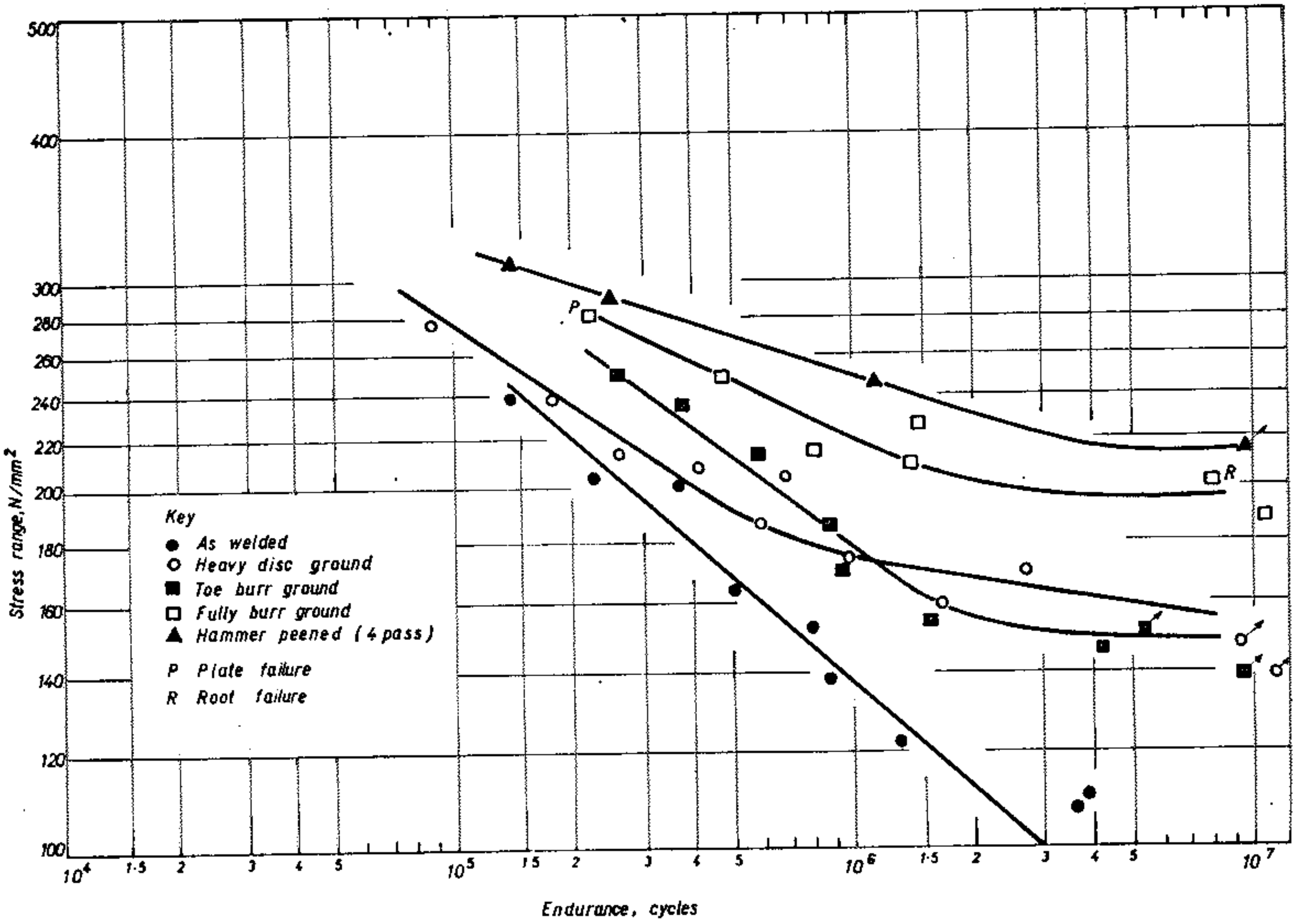

Fig.10. Results for specimens fabricated from BS 4360 Grade 43A.

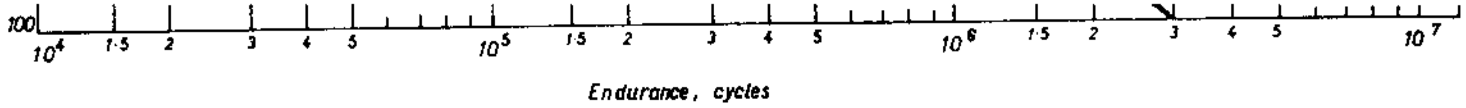

Fig.10. Results for specimens fabricated from BS 4360 Grade 43A.

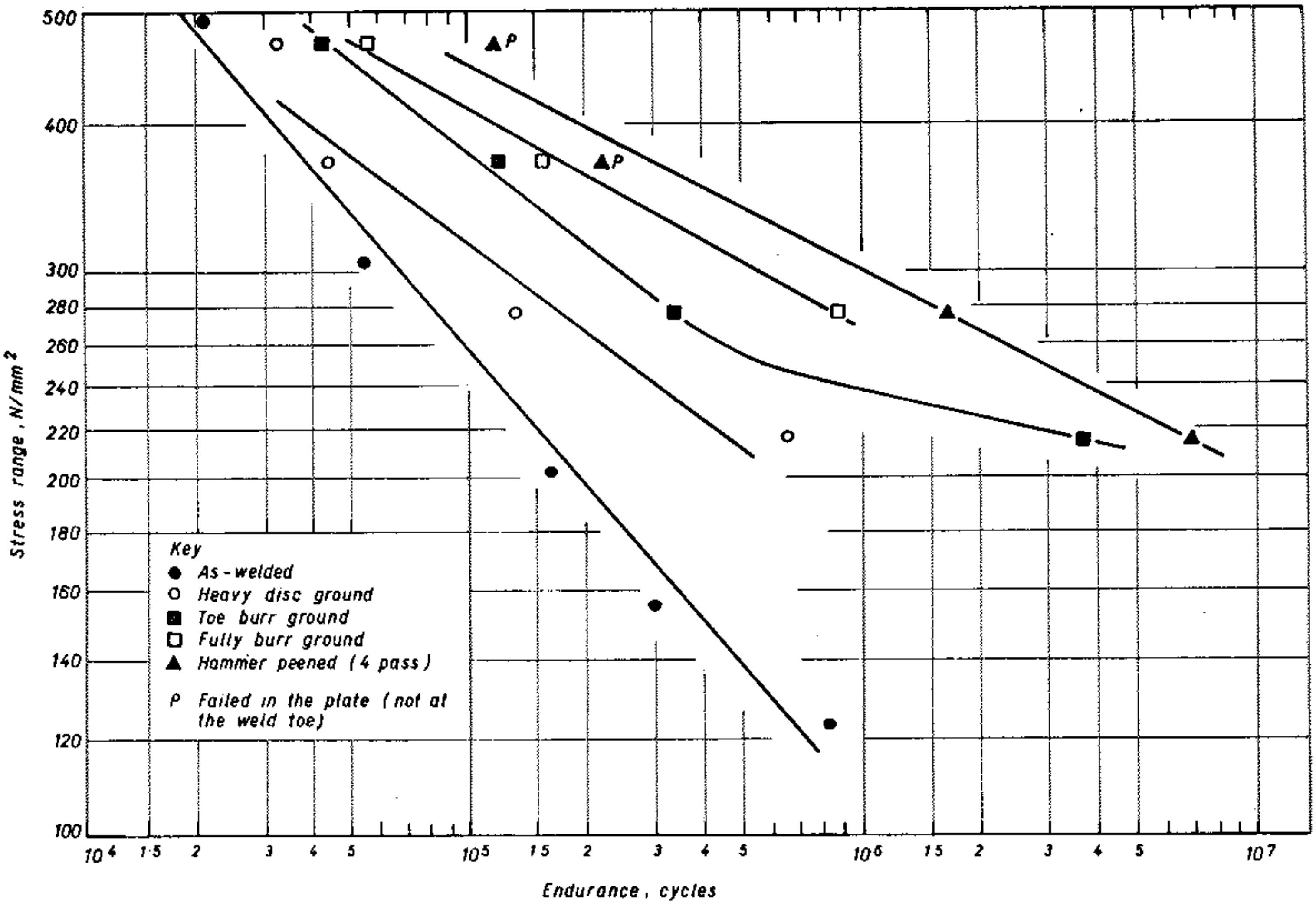

Fig.11. Results for specimens fabricated from high strength steel.

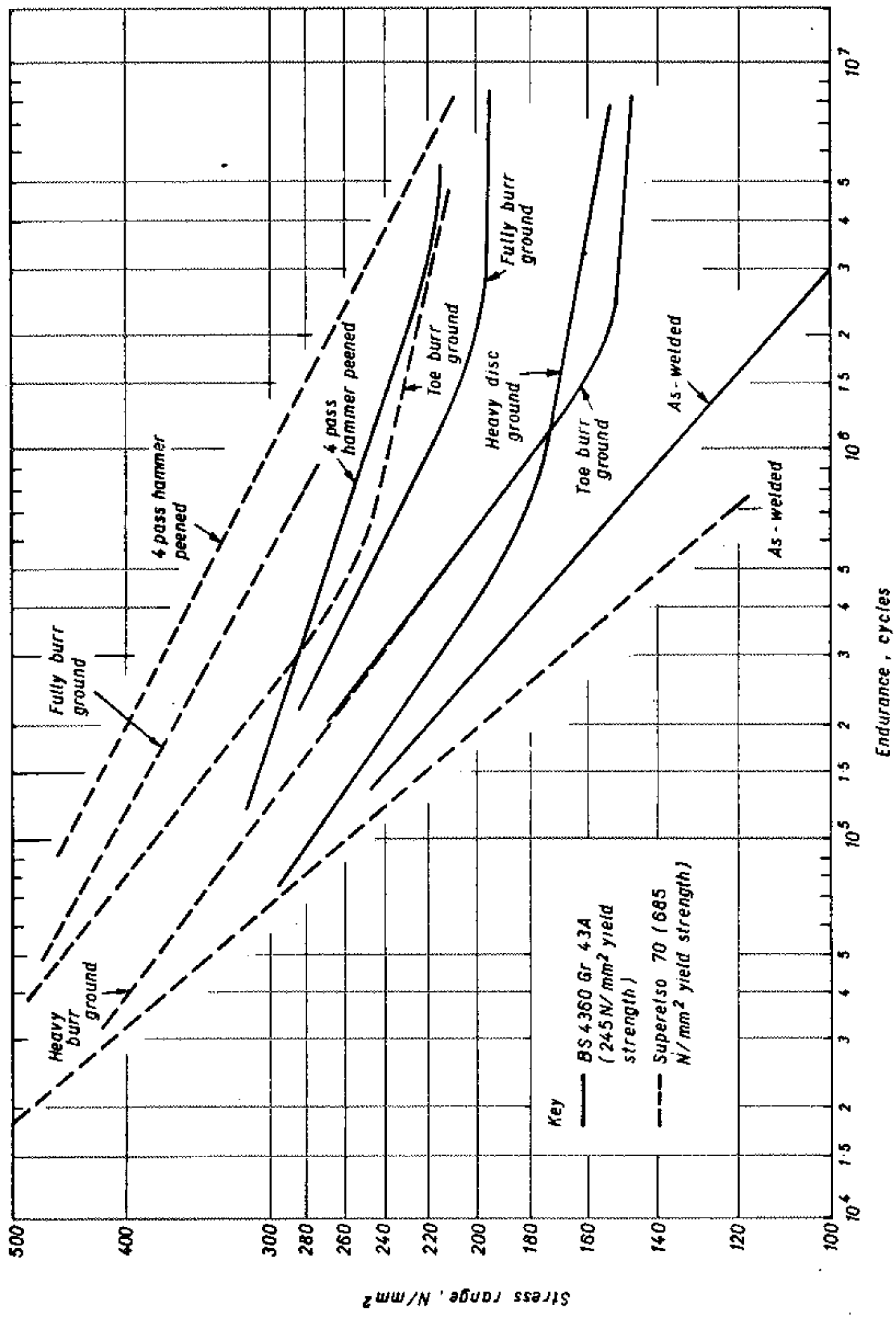

Fig. 12. Comparison between BS 4360 Grade 43A and high strength steel.

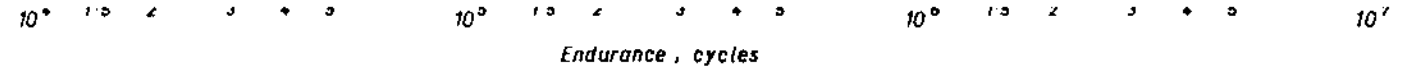

Fig. 12. Comparison between BS 4360 Grade 43A and high strength steel.

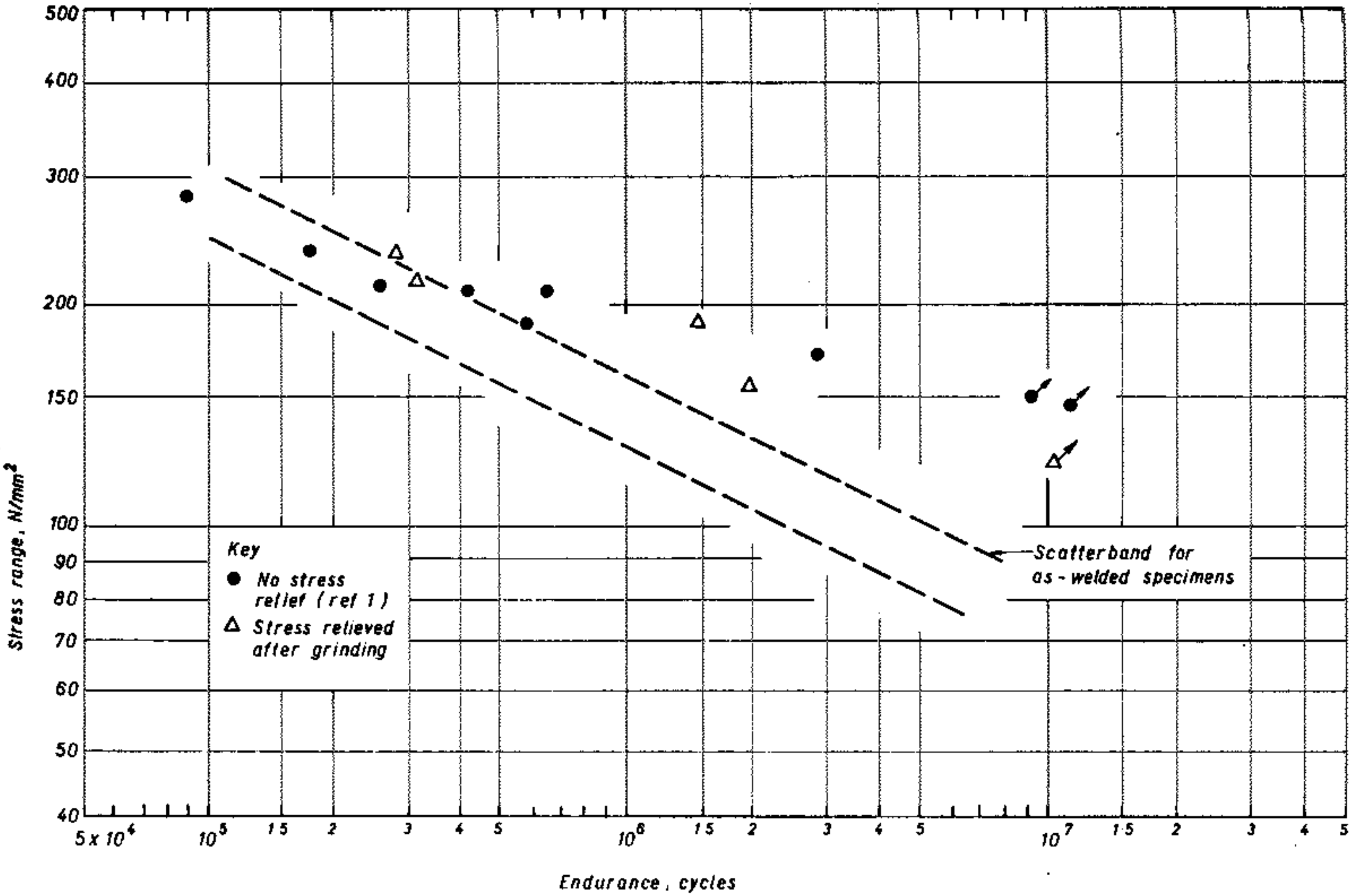

Fig. 13. The effect of stress relieving after disc grinding.

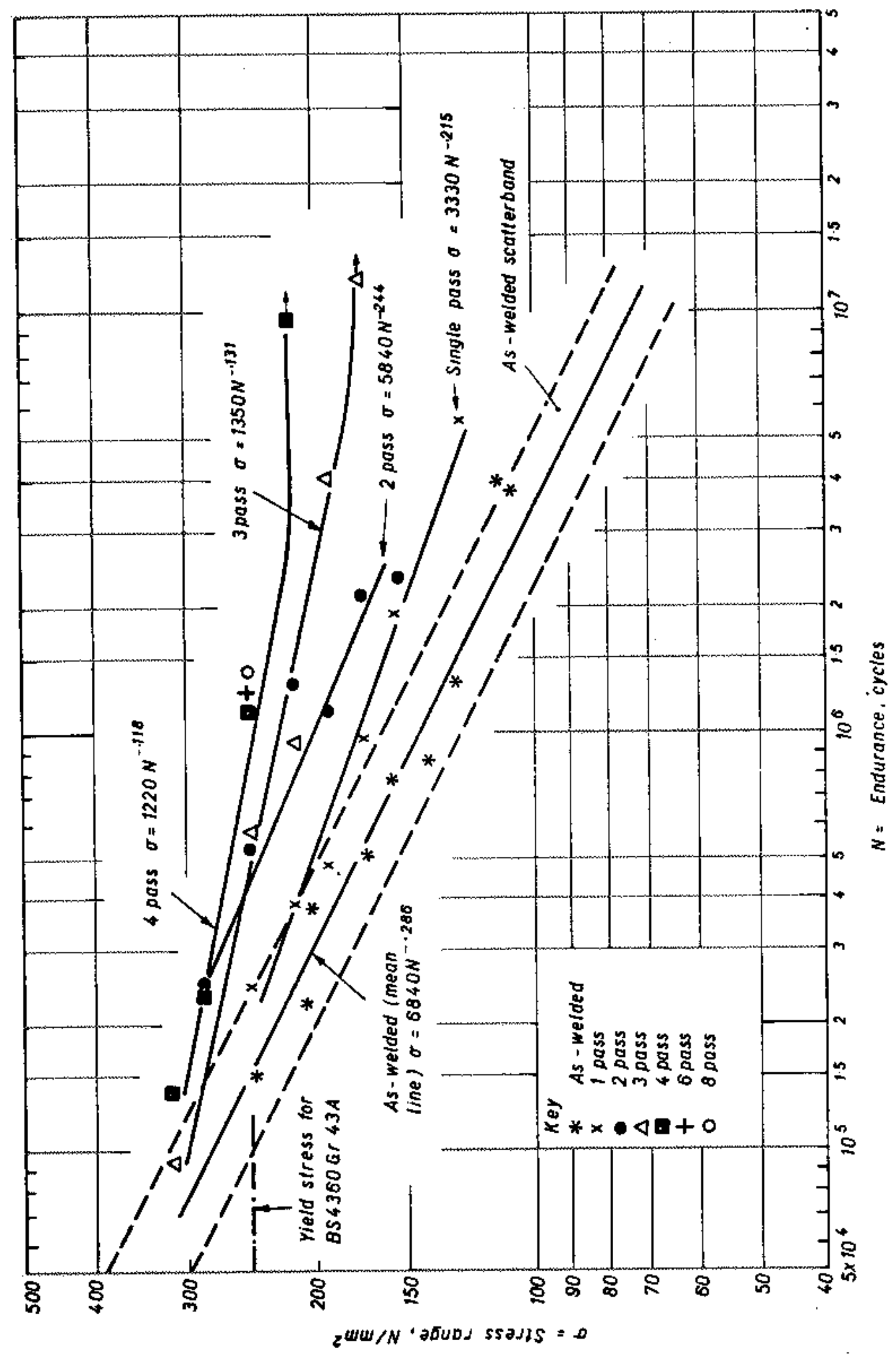

Fig. 14. Results for as-welded and peened specimens.

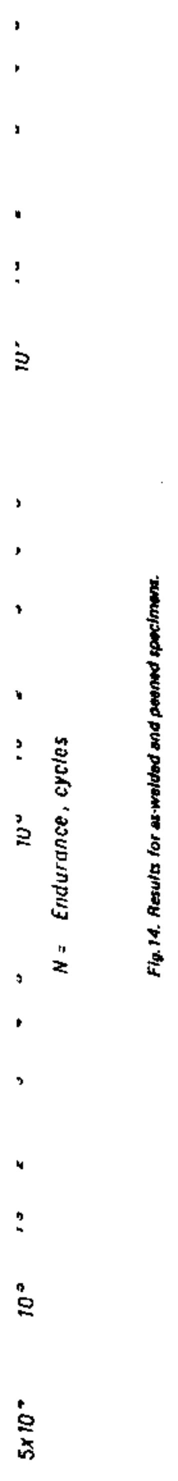

Fig.14. Results for as-welded and peened specimens.

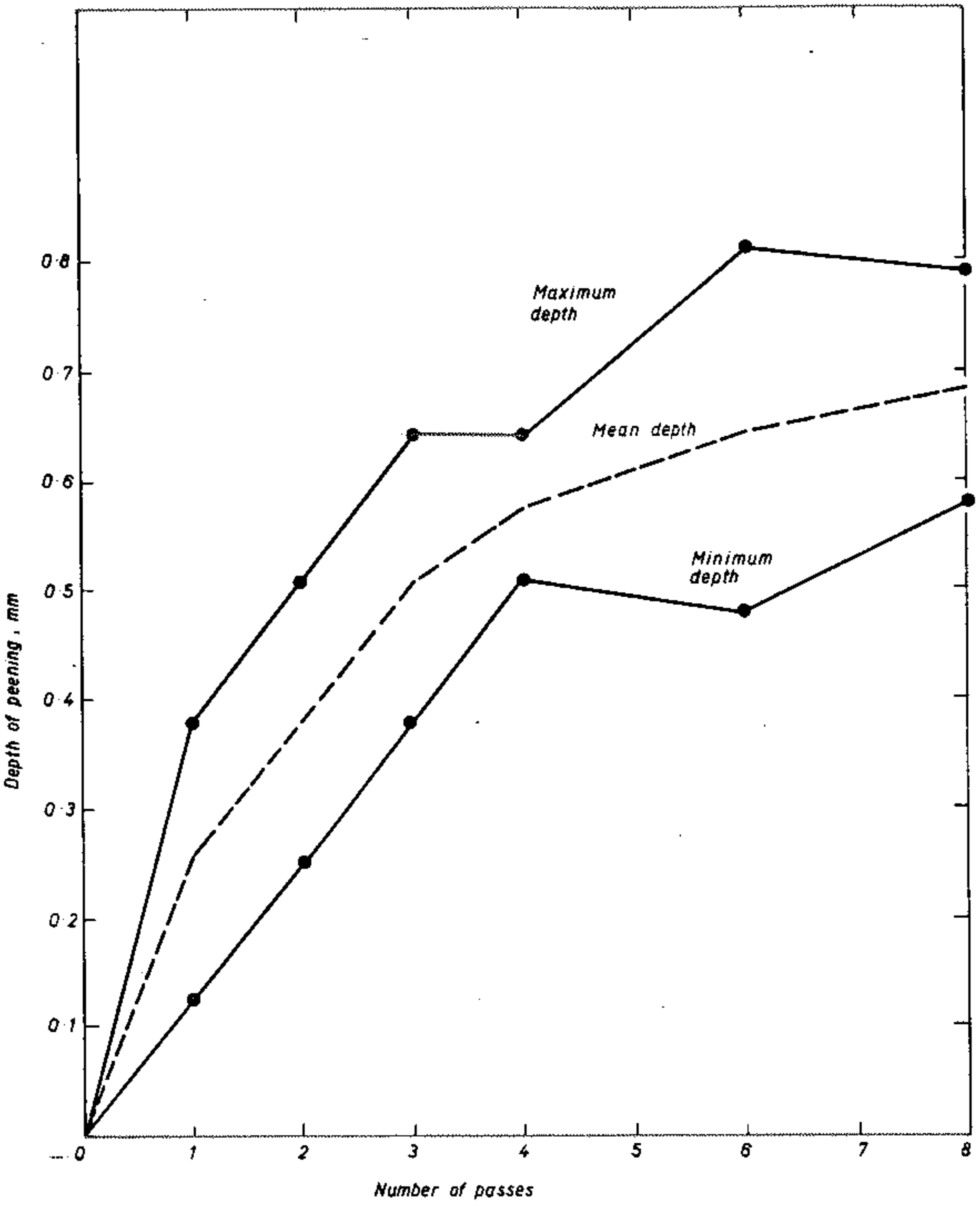

Fig.15. Depth of peening on parent plate v. number of passes.

WRI File

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IMPROVING THE FATIGUE STRENGTH OF FILLET WELDED JOINTS BY GRINDING AND PEENING

Abstract

As an extension to earlier work, tests have been carried out on transverse non-load-carrying fillet welded specimens fabricated from both BS 4360 Grade 43A and high strength steel (685N/mm^2 yield strength). Three grinding techniques have been studied and these are designated as follows:

i. Heavy disc grinding
ii. Toe burr grinding
iii. Full burr grinding

In addition, an investigation has been carried out into the effect of peening the weld toe region, with particular emphasis placed on the number of passes of the peening hammer along the weld.

All the techniques gave improved fatigue performance, with 4-pass hammer peening resulting in the greatest improvement as well as being the cheapest method of operation.

Keywords

FILLET WELDS; GRINDING; PEENING; WELDED JOINTS; FATIGUE STRENGTH; CARBON MANGANESE STEELS

AMELIORATION DE LA RESISTANCE A LA FATIGUE DES JOINTS SOUDES EN ANGLE EN MEULANT ET EN MARTELANT

Sommaire

Comme suite à des travaux antérieurs, des essais ont été réalisés sur des éprouvettes transversales soudées en angle non porteuses de charge fabriquées en acier BS 4360 Qualité 43A et de grande résistance (limite élastique 685N/mm^2). Trois techniques de meulage ont été étudiées et sont décrites comme suit:

i. Meulage disque lourd
ii. Meulage ébarbure extrémité
iii. Meulage ébarbure compléte

De plus, une enquête a été poursuivie sur l'effet de martelage de l'extrémité d'une soudure, en soulignant en particulier le nombre de passes du marteau sur la soudure.

Toutes les techniques ont donné une performance améliorée de la fatigue, avec martelage 4-passes au marteau résultant dans l'amélioration la plus nette et aussi représentant la méthode la meilleure marché.

Mots clefs

SOUDURES EN ANGLE; MEULAGE; MARTELAGE; JOINTS SOUDES; RESISTANCE A LA FATIGUE; ACIERS C-Mn

DAUERFESTIGKEITSAUFBESSERUNG VON KEHLNAHTGESCHWEISSTEN VERBINDUNGEN DURCH SCHLEIFEN UND NACHHAMMERN

Kurzbericht

Als Fortsetzung früherer Untersuchungsarbeiten unternahm man Versuche mit nicht-lasttragenden stirnkehlnahtgeschweissten Versuchsproben, die aus BS 4360 Grad 43A und hochfestem Stahl (Dehngrenze 685N/mm^2) hergestellt waren. Es wurden, wie nachstehend beschrieben, drei Schleifmethoden untersucht:

i. Hochleistungsabrichtschleifen
ii. Nahtübergang-Abgratschleifen
iii. Voll-Abgratschleifen

Zusätzlich ist die Wirkung eines Nachhämmerns der Nahtübergangzone untersucht worden, wobei man besonders auf die Anzahl der Durchläufe achtete, die vom Nachschlaghammer die Schweissung entlang gemacht wurden.

Die Methoden ergaben alle eine bessere Ermüdungsperformanz, wobei 4-Durchlauf-Nachhämmern die grösste Aufbesserung herbeiführte und sich auch als die billigste Arbeitsmethode erwies.

Schlüsselwörter

KEHLNAHTSCHWEISSUNGEN; SCHLEIFEN; KALTHÄMMERN; SCHWEISSNAHTVERBINDUNGEN; DAUERFESTIGKEIT; KOHLENMANGANSTÄHLE