THE EFFECT OF POST-WELD TREATMENTS ON FATIGUE AT FILLET WELDED ATTACHMENTS

1. INTRODUCTION

This Item provides information on the effect of post-weld treatments on the as-welded fatigue strength of non-load-carrying longitudinal and transverse fillet welded attachments to steel plates subjected to axial fatigue loading. The attachments covered by this Item are transverse fillet welded attachments, longitudinal stiffener and flange type attachments and wing butt welds, as illustrated in Sketch 3.1.

The fatigue strengths at fillet welded attachments in the as-welded condition are given in Items Nos 75016 and 76007. Where the as-welded fatigue strength is unsatisfactory, redesign is the best solution, and post-weld treatment should be used only when redesign to give improved geometry and/or lower stresses is not practically or economically feasible.

2. NOTATION

K	elastic stress concentration factor based on stress in loaded plate (at weld toe for transverse attachments and at end of weld run for longitudinal attachments)		
P	load applied to plate (see Sketch 3.1)	N	lbf
R	stress ratio = S_{min}/S_{max} = $(S_m - S_a)/(S_m + S_a)$		
S_a	alternating stress (half range) in loaded plate	N/m^2	lbf/in^2
S_m	applied mean stress in loaded plate	N/m^2	lbf/in^2
S_{min}	minimum stress $(S_m - S_a)$ in loaded plate	N/m^2	lbf/in^2
S_{max}	maximum stress $(S_m + S_a)$ in loaded plate	N/m^2	lbf/in^2
S_y	yield stress	N/m^2	lbf/in^2

Both SI and British units are quoted.

3. GENERAL PRINCIPLES

As-welded joints contain a highly localised system of residual stresses resulting from internal constraints arising during cooling of the weld. Experience shows that these stresses in the critical regions at the weld toe and the ends of weld runs are often tensile. Residual stresses in the direction of welding are high, usually of the order of the material yield strength, whereas stresses at 90 degrees to the direction of welding are not necessarily of this magnitude but depend on plate thickness. In thin plate the temperature during cooling is reasonably uniform through the thickness of the plate and the resulting transverse and through thickness stresses are likely to be small although stresses along the weld may be high. In thicker plates the temperature differences are more pronounced and the larger is the section that remains relatively cool during welding the higher are the residual stresses in the region of the weld. Therefore in very thick joints the transverse and through thickness stresses will be of the order of the material yield strength. Because of this the plate thicknesses are given on the figures.

Longitudinal fillet welded attachments are stressed along the line of the weld. Since the residual stress in this direction is of the order of yield, any applied loading will cause local yielding in the region of the stress concentration at the end of the weld run during the first few load cycles. This causes the actual stress experienced in the critical region to cycle between the yield stress and the yield stress less the local stress range, that is from S_y to $(S_y - 2KS_a)$.

In transverse fillet welded attachments the joint is loaded at 90 degrees to the welding direction. The maximum stress developed at the stress concentration at the weld toe is the sum of the residual stress and $K(S_m + S_a)$. If this sum exceeds the yield stress, S_y, local yielding will occur and, locally, subsequent cycles will range from S_y to $(S_y - 2KS_a)$. In thinner joints the residual stresses tend to be low and hence low applied stresses may not cause local stresses to exceed yield.

The condition where the residual and applied stresses are high enough to cause local yielding in critical regions is termed the yield limited condition. Where this condition applies the stress experienced at stress concentrations will cycle between the yield stress and the yield stress less the applied stress range irrespective of applied mean stress or the material yield strength. If however the residual stresses are low, as in the case of transverse fillet welded joints in thin plate, or can be brought to a low level by post-weld treatment, then the effects of mean stress may become evident. If the mean stress is such that, at the stress range applied, the maximum local stress is less than yield the fatigue life will be greater than that found if the same stress had caused the yield limited condition. If the yield limited condition does not apply then lowering the mean stress applied will give an increase in endurance; the effect of mean stress will be more noticeable at lower alternating stresses. The effect of the joint being out of the yield limited condition is to rotate the fatigue curve for as-welded joints anticlockwise, see Sketch 5.1. The point about which this rotation occurs is dependent upon the residual and applied stress but for cases where the applied stress cycle is fully tensile this rotation is about the material’s yield stress, see Sketch 5.2.

Improvements in fatigue strength can be brought about both by reducing the stress concentration factor, K, and/or reducing the residual stress. The fatigue strength can also be improved by removing defects at points of stress concentration from which fatigue cracks may grow to cause failure.

Post-weld treatments fall into three categories:

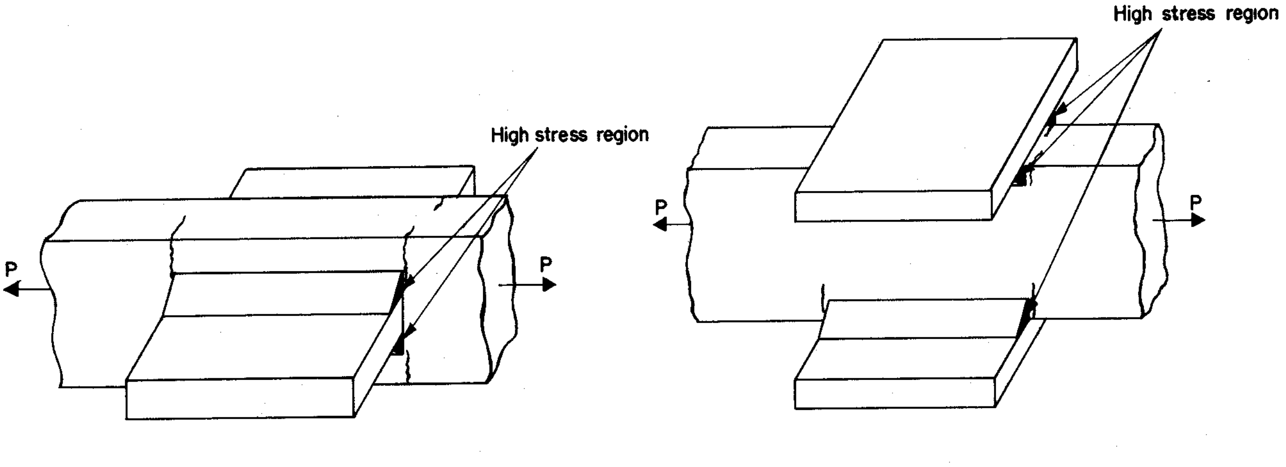
1. shape changing methods, for example weld profile grinding,

2. mechanical methods, for example peening or prior overloading, and

3. thermal methods such as stress relieving.

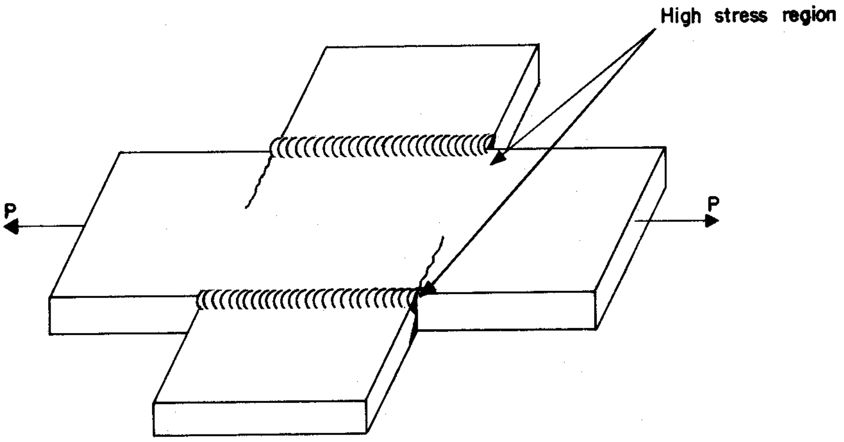
The following sections deal with the above three categories in turn. Treatments for which insufficient data are available or in which application methods are ill-defined are dealt with separately in Section 7. Summaries of these processes and their effects are given in Table 9.1. Improvement in fatigue strength may not always be the main reason for applying these processes.

Combinations of processes can be used as long as care is taken to apply them in the correct order. Shape changing processes are always beneficial as they reduce K and hence the local stress range. The effects of processes that alter the state of residual stress are not always so. This is because applied stresses can be such that even after treatment the yield limited condition applies or because subsequent treatment can remove material containing a beneficial stress system.

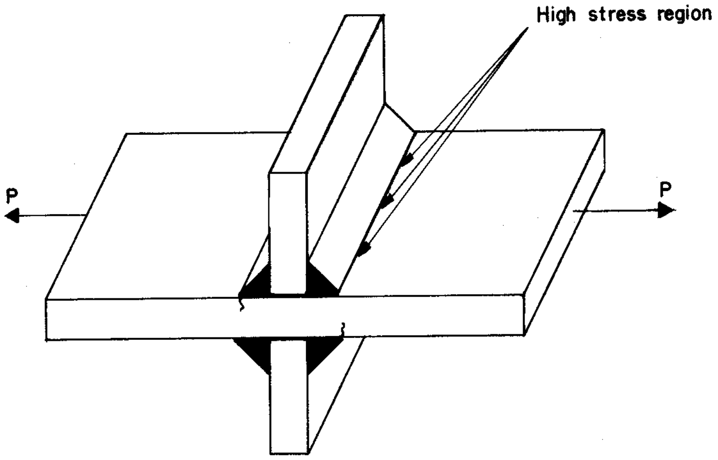


a) Longitudinal stiffener type fillet welded attachment

b) Longitudinal flange type fillet welded attachment



c) Wing-butt welded attachment



d) Transverse fillet welded attachment

Sketch 3.1 Attachments covered by this Item

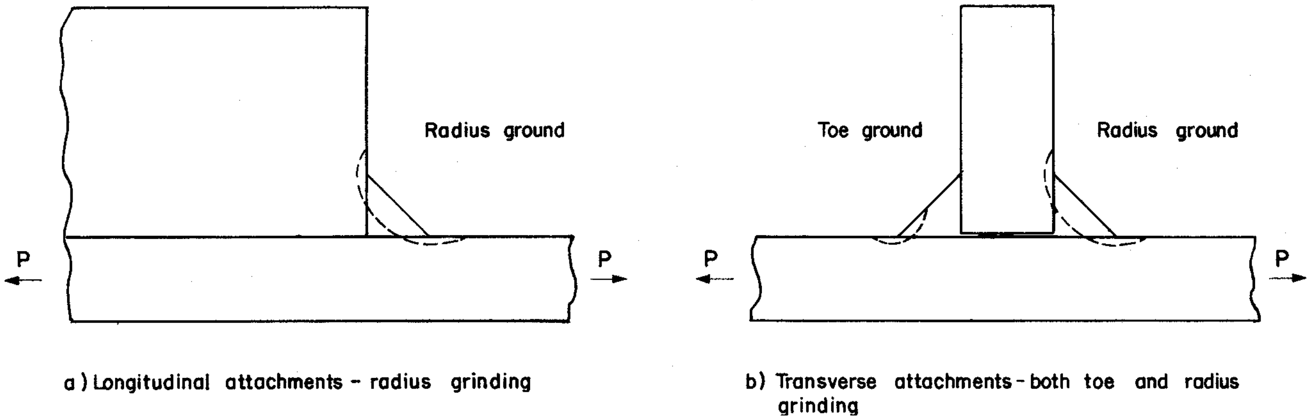
The improvements produced are determined by the method used, process variables and, to a great extent, by the skill and efficiency of the operator. **Care must be taken when applying these methods in practice as application of the wrong method (or the correct method applied in the wrong position or the wrong order) can reduce the fatigue strength.**

4. SHAPE CHANGING METHODS

The purpose of a shape changing process, either grinding or tungsten-inert-gas welding, is to increase the plate-to-weld transition radius, so reducing the stress concentration and hence increasing fatigue strength, and also to remove surface defects likely to be sites for initiation of fatigue cracks at critical regions of the joint.

4.1 Grinding of the Weld Profile

This process can be applied to both transverse and longitudinal welds. Grinding can be either light, involving grinding of only the transition region between the plate and weld materials, or full, involving radius grinding at the end of the weld run in longitudinal joints and along the toe of the weld in transverse joints (see Sketch 4.1).



a) Longitudinal attachments – radius grinding

b) Transverse attachments – both toe and radius grinding

Sketch 4.1 Illustrating the application of grinding to fillet welded attachments (exaggerated for clarity)

Since grinding alters the stress concentration in critical regions, improvements are produced at all applied stress levels so, in effect, the fatigue curve is lifted, without rotation. Improvements of 50 per cent in fatigue strength can reasonably be achieved by correct application of this method, see Figures 1 and 2, but even greater improvements are possible.

Grinding is of particular benefit in transverse fillet joints where even light grinding gives marked improvement in fatigue strength. Figure 1 gives data for transverse joints that have been ground and compares these with data for as-welded joints (from Item No. 75016). Light grinding has little effect at the ends of longitudinal weld runs as a severe stress concentration remains, associated with the change in stiffness, irrespective of the state of the ends of the weld run. Thus in longitudinal joints the stress concentration, coupled with the high residual stress is enough to give the yield limited condition even after light grinding, and reduction of applied mean stress has little effect on fatigue strength. Figure 2 gives data for longitudinal joints that have been radius ground such that the end of the attachment is contoured along with the ends of the weld run, and compares this with data for as-welded joints (from Item No. 76007).

4.2 Tungsten-Inert-Gas (TIG) Weld Run at the Weld Toe

This method consists of an additional run over the weld toe with a non-consumable tungsten electrode shielded with an inert gas which, although depositing no new weld material, remelts the surface material in the region of the weld toe. On solidification a smooth, larger, transition radius is formed which is relatively free of defects. This method is particularly useful for transverse welds. Data for joints treated using this process are given in Figure 1. The degree of improvement is the same as that produced by grinding.

5. MECHANICAL METHODS

Mechanical methods involve changing the residual stress state at the critical regions of welds. Two processes of this kind are peening and heavy shot blasting of the critical regions which causes plastic yielding and leaves the surface of the weld in a state of residual compressive stress. These processes may also lead to a beneficial increase in the radius of transition, some defects are removed and some work hardening of the weld material occurs thus giving an increase in fatigue strength. Another process is prior overloading which gives static tensile stressing in the direction of the intended fatigue loading such that yield is exceeded locally. On relaxation the local stresses are reduced and may become compressive.

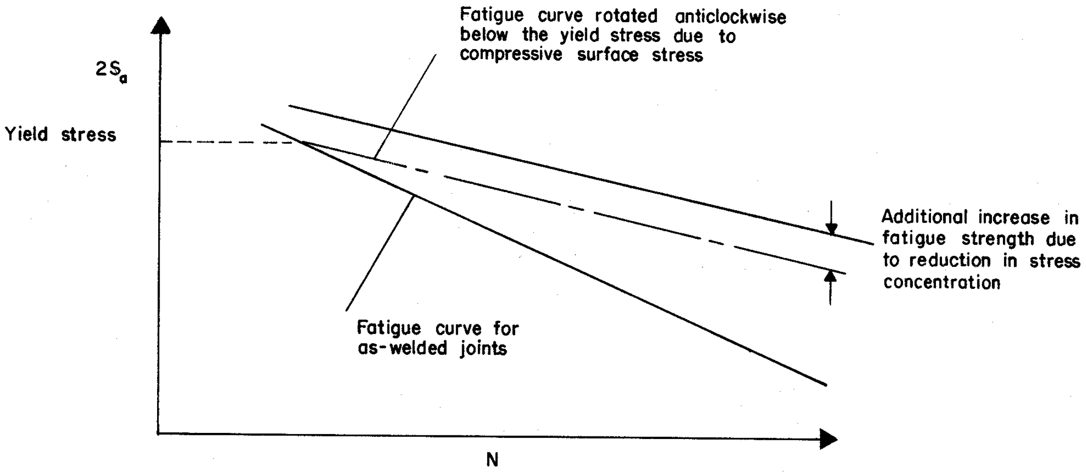
Methods which at present are unsatisfactorily defined are vibrational stress relief, causing reduction of peak residual stresses, and spot pressing, involving application of concentrated compressive load adjacent to points of stress concentration in longitudinal joints. These methods are discussed briefly in Section 7.

5.1 Peening

Peening is useful for both longitudinal and transverse welds. Improvements in performance depend upon the magnitude of the compressive stress introduced into the surface layer of the welds by the peening tool. The harder the joint is peened the greater the improvement found. A solid tool produces greater improvement than a multi-point tool. The effect of peening using a solid tool on transverse welds is given in Figure 3 and for longitudinal welds in Figure 4.

In transverse welds the compressive stress induced is sufficient to take the joint out of the yield limited condition, see Section 3. In longitudinal welds the fatigue curve was found to rotate. No difference in fatigue strength for attachments welded around the ends and those not welded around the ends was found.

Peening applied after grinding gives added improvement but grinding after peening simply removes the beneficial effects of the peening process.



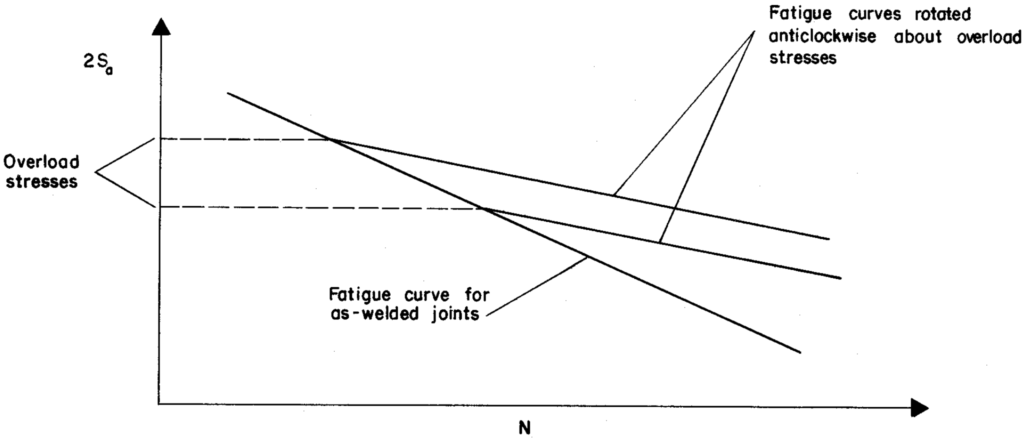
Sketch 5.1 Expected effect of peening on the fatigue behaviour of fillet welded attachments

5.2 Shot Blasting

In this process the surface of the weld is blasted with hard rounded particles. The effectiveness of this process is determined by shot size and velocity, shot hardness, angle of strike and duration of application. Increasing the size and velocity of the shot increases the depth below the surface to which compressive stress is induced but has little effect upon the magnitude of the compressive stresses which is about half the material compressive yield strength. Shot blasting after grinding gives added improvement but not vice versa (see Section 5.1).

5.3 Prior Overloading

In this method the whole component including the joint is given a static tensile loading in the intended direction of loading such that the material yields locally in regions of stress concentration. When the overload is removed these regions are in a state of lower or even compressive residual stress. The higher the stress used to overload the component, **without deleterious effects elsewhere**, the greater the improvement, see Sketch 5.2. This method is particularly effective for longitudinal attachments but can be used on transverse joints.



Sketch 5.2 Expected effect of prior overloading on fatigue behaviour of fillet welded attachments

6. THERMAL METHODS

These methods require application of heat which reduces the value of residual stress in critical regions so as to increase the fatigue strength at low applied mean or alternating stress levels by avoiding the yield limited condition.

For spot heating see Section 7.

6.1 Stress Relief

Stress relief can be applied to both longitudinal and transverse joints although fatigue improvement may not be the primary reason for the treatment. The component is heated to a uniform temperature below the microstructural transformation temperature, usually around 600 to 650°C, and uniformly furnace cooled (to prevent distortion and formation of further stresses). The rise in temperature lowers the yield strength and residual stresses originally above this value are redistributed by a rapid creep mechanism. The effect of stress relief is that, owing to lower residual stresses, low mean and alternating stresses may not create a yield limited condition, see Section 3. Hence low alternating stress and low or compressive mean stress will give a fatigue strength above that of an as-welded joint, for example, see the $R = -4$ data of Figure 5 which gives data for stress relieved longitudinal fillet welds. No data have been found for transverse joints.

Local stress relief in situ is possible but great care must be taken to avoid deleterious stresses elsewhere.

It is possible to increase the fatigue strength subsequent to stress relief by applying other processes, for example, peening after stress relief.

6.2 Heating and Rapid Quench

This process sets up a high compressive stress in the surface layers in critical regions of both longitudinal and transverse joints. The whole area around the weld toe in transverse joints and the end of the attachment in longitudinal joints is heated to around 550°C and then water is sprayed over the region where the compressive stress is required. This cools only the surface which tries to contract and yields in tension; the compressive stress at the surface is produced by subsequent contraction of the hot metal underneath the surface. Correctly applied the method can give significant improvement in fatigue strength. Using a spray rather than a water bath quench gives a much greater degree of improvement. Data for joints treated with this process are given in Figure 6.

7. PROCESSES FOR WHICH FEW DATA ARE AVAILABLE OR FOR WHICH APPLICATION METHODS ARE ILL-DEFINED

This section deals with post-weld treatments about which there are insufficient data or where the techniques used are subject to uncertainty and where incorrect application could have deleterious effects. These are vibrational stress relief, which may be of little use in improving fatigue, and spot pressing and spot heating where the location of application and other practical aspects of the process are not clear.

7.1 Vibrational Stress Relief

This process involves subjecting the component to a random vibrating load that causes local yield at points of high stress concentration. The main use of this process is in reducing residual stress to achieve dimensional stability.

7.2 Spot Pressing

This method involves application of a localised compressive load to the joint in the through thickness direction such that the critical region at the end of the weld run is put in a state or residual compression. This brings the joint out of the yield limited condition, see Section 3. The residual in-plane radial compressive stress that is created in the pressed region is balanced by a circumferential tensile stress around the pressed spot and hence care must be taken in positioning the spot. For location and size of these pressed areas and the loads involved see the derivations quoted on Figure 6 and Derivation 9. Data for joints treated using this process are given in Figure 6.

The primary use of this process is in stopping fatigue cracks that are already growing.

7.3 Spot Heating

This method involves application of heat, usually with an oxy-acetylene torch, to an area of the plate surface adjacent to the ends of weld runs in longitudinal attachments such that after cooling these critical regions are in a state of residual compression and no longer in the yield limited condition, see Section 3. The heated spot yields in compression and on cooling is in a state or radial residual tensile stress. This stress is balanced by an in-plane circumferential compressive stress around the heated spot. It is in this compressive region that critical regions must be located. For location and size of these heated spots see the derivations quoted on the figures and Derivation 9. Data for attachments treated using this process are given in Figure 6.

8. DERIVATION

This section lists selected sources that have assisted in the preparation of this Item.

1.	PUCHNER, O.	Increase of the fatigue limit of plates and beams with welded-on gusset plates by local heating. International Institute of Welding, London, UK, Document XIII Series, No. 179, 1959.
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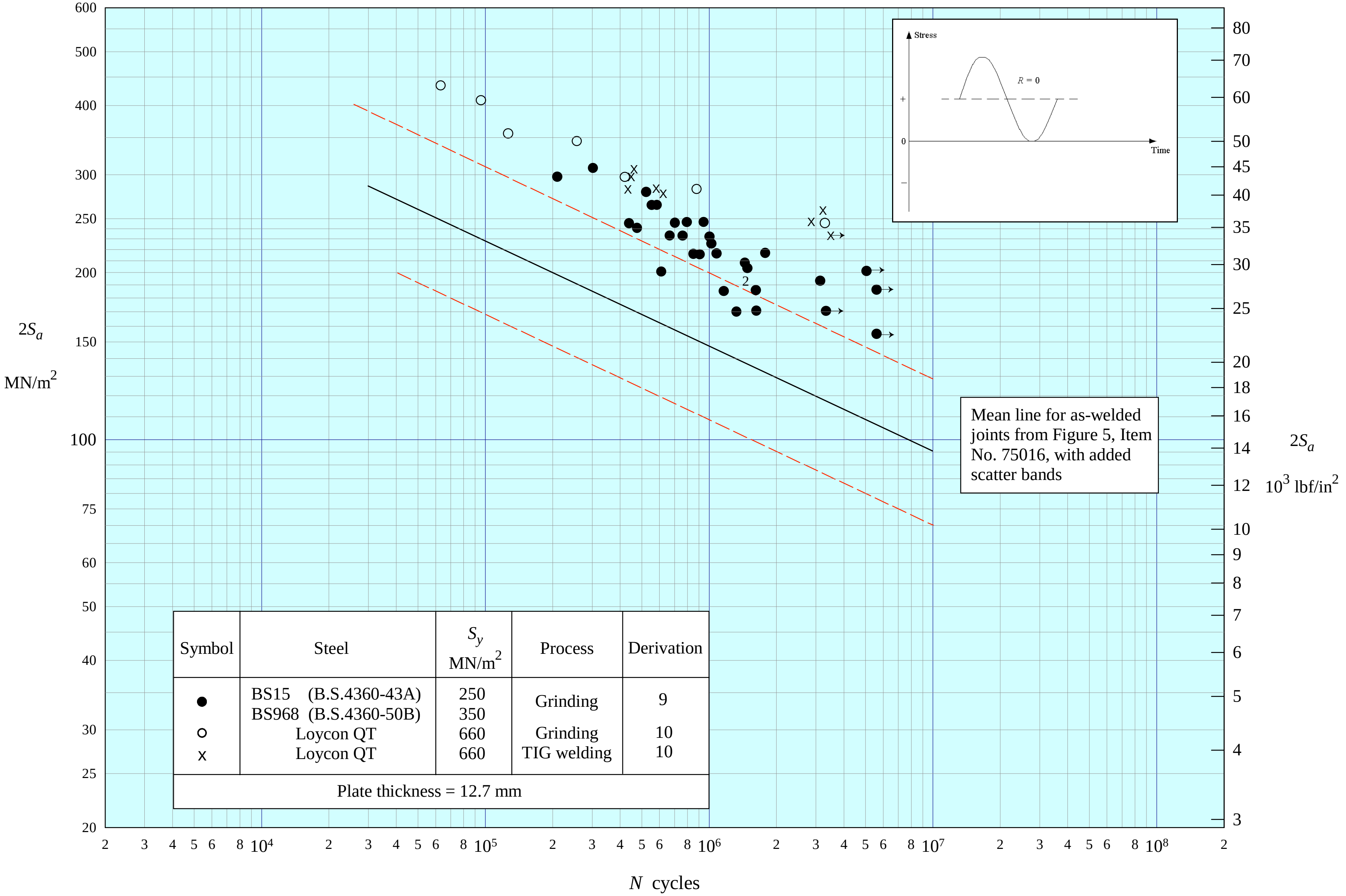
3.	GURNEY, T.R.	Influence of residual stresses on fatigue strength of plates with fillet welded attachments. *Br. Weld. J.*, London, UK, Vol. 7, No. 6, pp. 415-431, June 1960.
4.	NACHER, A.	Influence of local heating and of surface peening on fatigue behaviour of welded joints and details. International Institute of Welding, London, UK, Document XIII Series, No. 255, 1960.
5.	MOORTGAT, M.	Local heating and its influence on fatigue behaviour of welded cross-shaped test-specimens. International Institute of Welding, London, UK, Document XIII Series, No. 284, 1961.
6.	GURNEY, T.R.	Further fatigue tests on mild steel specimens with artificially induced residual stresses. *Br. Weld. J.*, London, UK, Vol. 9, No. 11, pp. 746-613, November 1962.
7.	GURNEY, T.R.	Exploratory tests on fillet welded specimens subjected to prior overloading. *Br. Weld. J.*, London, UK, Vol. 10, pp. 516-526, October 1963.
8.	HARRISON, J.D.	Further techniques for improving the fatigue strength of welded joints. *Br. Weld. J.*, London, UK, Vol. 13, No. 11, pp. 642-647, November 1966.
9.	GURNEY, T.R.	*Fatigue of welded structures.* Chapter 11, Cambridge University Press, 1968.
10.	GURNEY, T.R.	The effect of grinding and peening on the fatigue strength of filled welded joints in two steels. *Br. Weld. J.*, London, UK, Vol. 15, No. 12, pp. 601-609, December 1968.
11.	HARRISON, J.D.	Techniques for improving the fatigue strength of welded high strength steels. Paper C 215/7/68, Conference on fatigue of welded Structures, Cambridge, UK, 1970.
12.	PARLANE, A.J.A.	Vibrational stress relief. *Weld. Inst. Res. Bull.*, London, UK, pp. 339-342, December 1977.

9. DATA

TABLE 9.1

Process	*How it works*	*To which joints it can be applied*[*]	*Fatigue strength achieved at 2×10^6 cycles $2S_a$*	*Percentage increase in fatigue strength over that of as-welded joints*	*Notes*
Shape Changing Methods					
Profile grinding	Produces concave weld profile, increases transition radius and removes defects	L	130 MN/m^2	40 – 50	Full radius grinding only. Improvements at all stress levels.
		T	160 MN/m^2	50	Full or light grinding. Improvements at all stress levels.
Tungsten-inert-gas (TIG) weld run at the weld toe	Produces concave weld profile, increased transition radius and removes defects	T	160 MN/m^2	50	Easy to apply
Mechanical Methods					
Peening	Induces compressive stress in surface layers. Improves weld profile. Work hardens surface	L T	–	Depends upon yield stress of plate material	Harder peening gives better improvement – solid tool is the most effective
Shot blasting	Same as peening	L T	–	Depends upon process variables	Few data available
Prior overloading	Reduces residual stress by causing local yielding	L T	–	Depends upon overload stress	More beneficial where low mean stresses are used
Thermal Methods					
Stress relief	Heating lowers yield stress allowing local yielding to occur. Reduces the residual stress	L T	–	Depends on mean stress used and material yield stress. Little effect if fully tensile loading applied	Benefits at low mean stress levels. Small specimens only. (Can be done on site.) Furnace cooling used. Care must be taken to avoid surface decarburisation
Heat and rapid quench	Induces compressive stress by quenching heated joint with spray. Hot interior contracts on cooling to give compressive stresses in surface	L T	–	Depends upon effectiveness of quench, mean stress used and yield stress. Improvements of over 100 per cent for mild steel at 2×10^6 cycles	Water spray must be used. Water bath is not so effective.
Ill-Defined Processes					
Vibrational stress relief	Involves applying random loading sequence to cause local plastic yield at stress concentrations	L T	–	Depends upon applied load cycle	This effect may occur in service. Used to stabilise dimensions
Spot pressing	Involves pressing spot to give region of local compression by local yielding	L	–	Depends upon design, load applied and material yield stress	Must be positioned at the end of the attachment. Method is of use in stopping cracks. Position of the spot very important
Spot heating	Involves heating spot which yields in tension giving balancing compressive stress outside the heated spot on cooling	L	–	Depends upon spot size and temperature used and material yield stress	Position of the spot very important

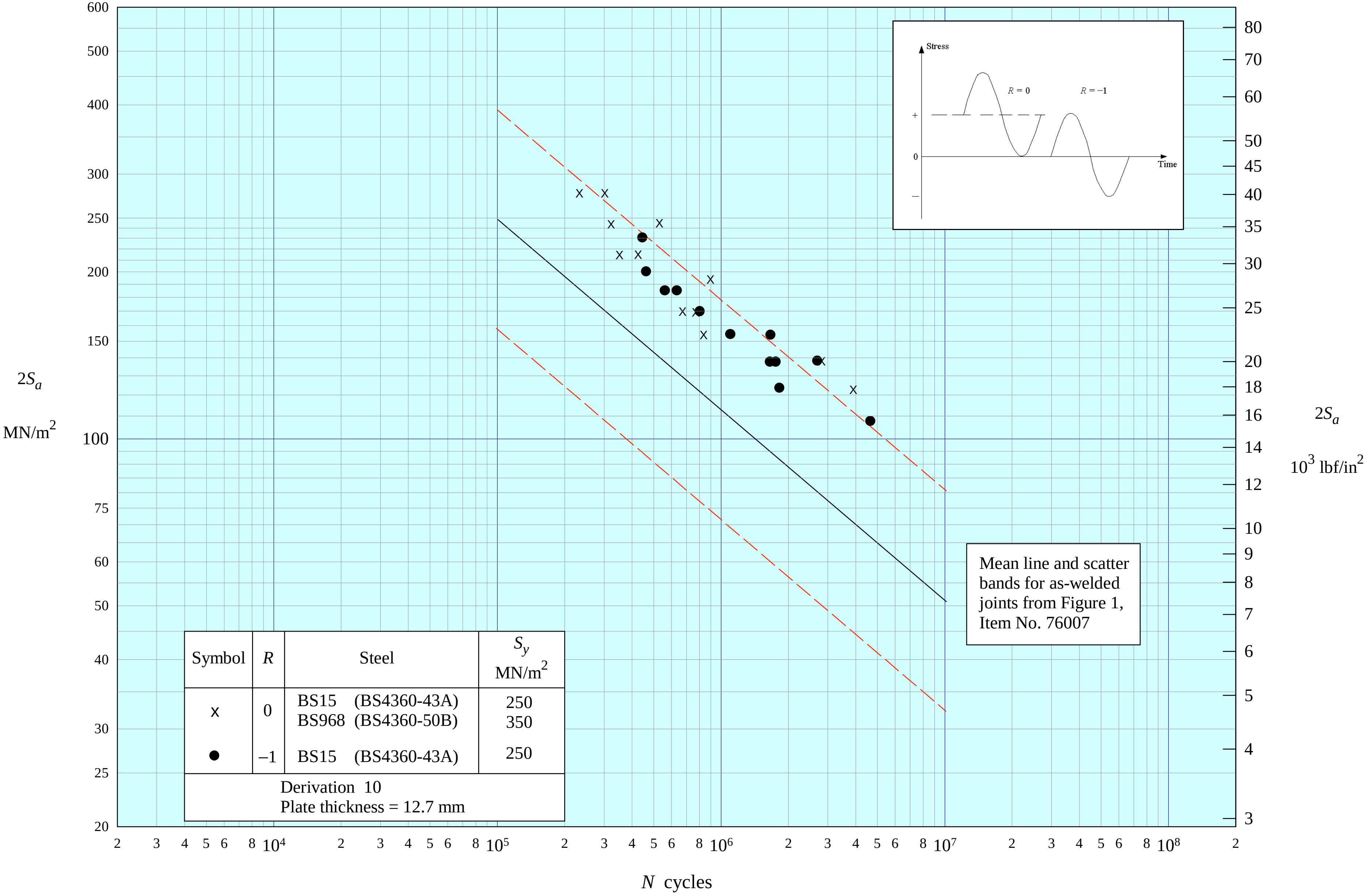
[*] L = Longitudinal; T = Transverse



Symbol	Steel	S_y MN/m^2	Process	Derivation
●	BS15 (B.S.4360-43A)	250	Grinding	9
	BS968 (B.S.4360-50B)	350		
○	Loycon QT	660	Grinding	10
x	Loycon QT	660	TIG welding	10

Plate thickness = 12.7 mm

FIGURE 1 EFFECT OF GRINDING AND TUNGSTEN-INERT-GAS WELDING ON FATIGUE STRENGTH AT TRANSVERSE FILLET WELDED ATTACHMENTS (R = 0)

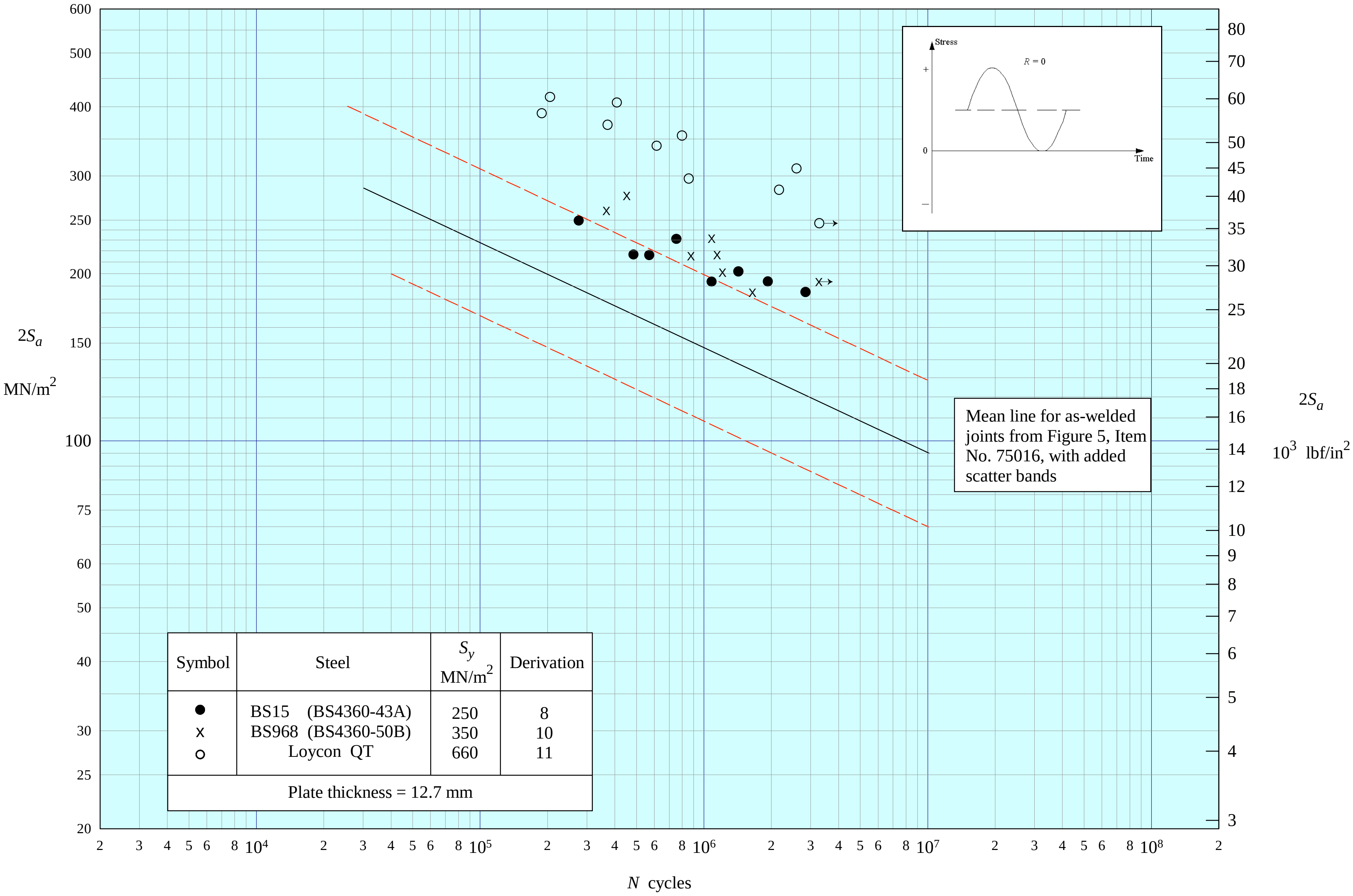


Symbol	R	Steel	S_y MN/m^2
x	0	BS15 (BS4360-43A) BS968 (BS4360-50B)	250 350
●	–1	BS15 (BS4360-43A)	250

Derivation 10
Plate thickness = 12.7 mm

Mean line and scatter bands for as-welded joints from Figure 1, Item No. 76007

FIGURE 2 EFFECT OF FULL GRINDING ON FATIGUE STRENGTH AT LONGITUDINAL FILLET WELDED ATTACHMENTS (R = 0 AND – 1)



Mean line for as-welded joints from Figure 5, Item No. 75016, with added scatter bands

Symbol	Steel	S_y MN/m^2	Derivation
●	BS15 (BS4360-43A)	250	8
x	BS968 (BS4360-50B)	350	10
○	Loycon QT	660	11

Plate thickness = 12.7 mm

FIGURE 3 EFFECT OF PEENING ON FATIGUE STRENGTH AT TRANSVERSE FILLET WELDED ATTACHMENTS ($R = 0$)

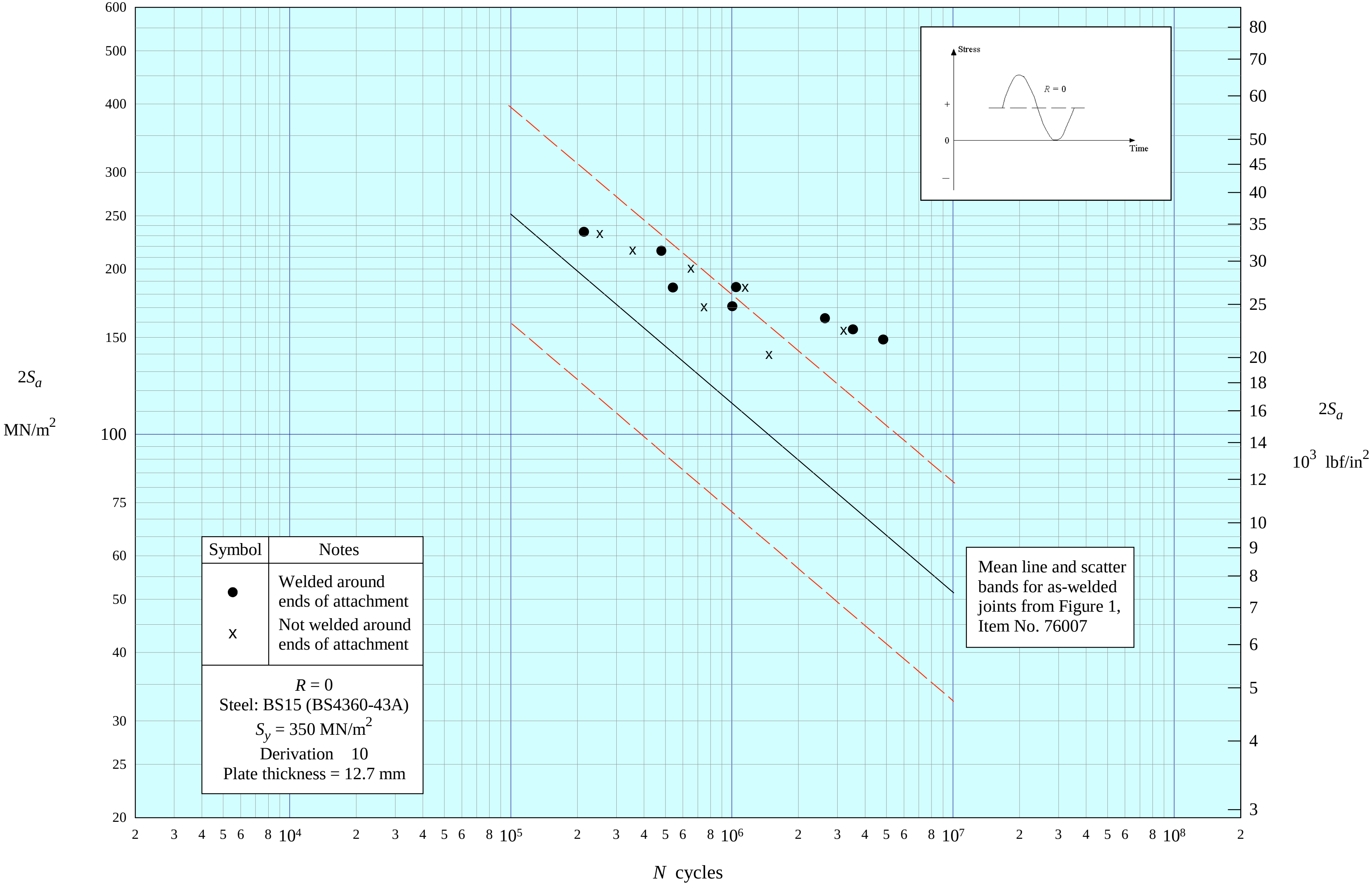


FIGURE 4 EFFECT OF PEENING ON FATIGUE STRENGTH AT LONGITUDINAL FILLET WELDED ATTACHMENTS ($R = 0$)

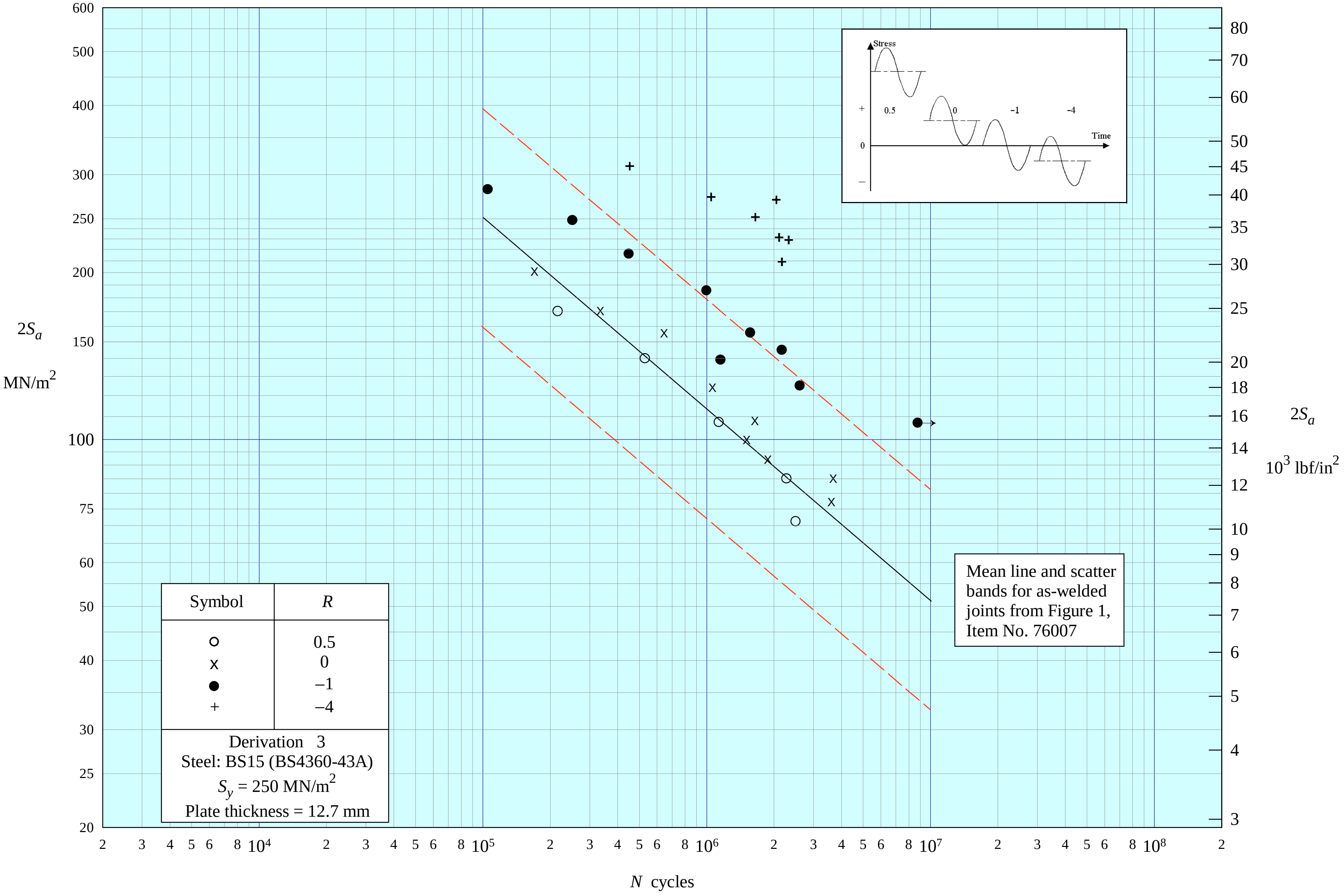


FIGURE 5 EFFECT OF STRESS RELIEF ON FATIGUE STRENGTH AT LONGITUDINAL FILLET WELDED ATTACHMENTS (R = 0.5, 0, –1 , –4)

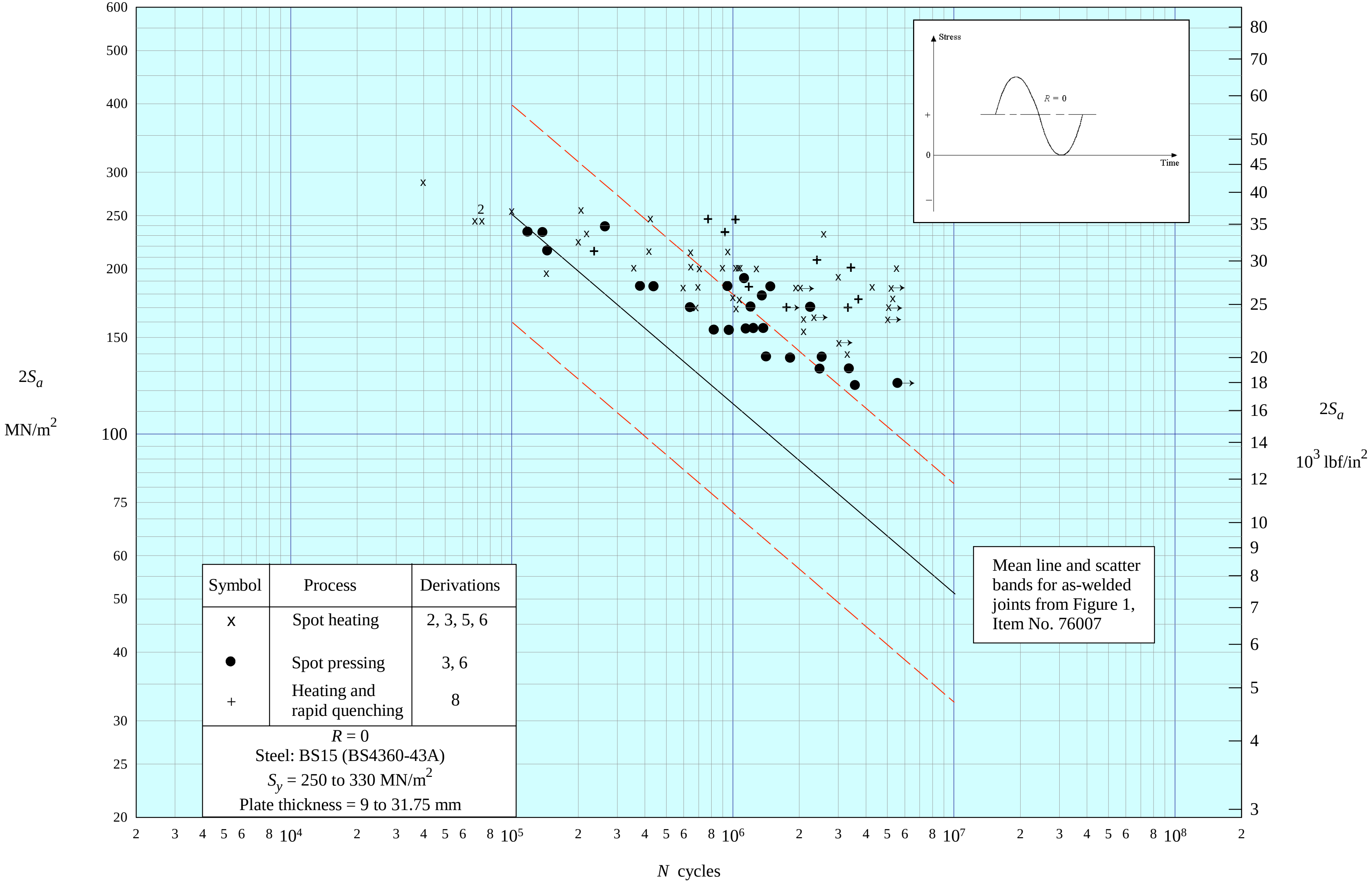


FIGURE 6 EFFECT OF SPOT HEATING AND SPOT PRESSING ON FATIGUE STRENGTH AT LONGITUDINAL FILLET WELDED ATTACHMENTS ($R = 0$)

THE PREPARATION OF THIS DATA ITEM

The work on this particular Item was monitored and guided by the Stress Analysis and Strength of Components Committee which first met in 1964 and now has the following membership:

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Dr C.E. Turner – Imperial College of Science and Technology.

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The work on this Item was carried out in the Strength Analysis Group of ESDU under the supervision of Mr M.E. Grayley, Group Head. The member of staff who undertook the technical work involved in the initial assessment of the available information and the construction and subsequent development of the Item was

Mr R.P. Sharp – Senior Engineer.