THE SPRING RESEARCH ASSOCIATION

THE INFLUENCE OF DECARBURISATION DEPTH ON THE FATIGUE STRENGTH OF A Si-Mn SPRING STEEL - A LABORATORY INVESTIGATION AND PRODUCTION RECOMMENDATIONS

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SUMMARY

The mechanism and measurement of decarburisation have been investigated. The influence of decarburisation depth on the fatigue strength of a Si-Mn spring steel has been examined, with the aim of providing a means of quantifying the effect. The use of controlled furnace atmospheres and protective coatings to eliminate decarburisation has been reviewed.

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1. INTRODUCTION

Decarburisation is an important factor involved in the premature failure of some spring materials during service.

The mechanism of decarburisation, the quantification of its influence on fatigue strength and possible methods of eliminating it are therefore of great importance to the spring manufacturer. These aspects have been examined and experimental work has been carried out to quantify the influence of decarburisation depth on fatigue strength, using a Si-Mn steel commonly employed in the spring industry.

1.1. The Mechanism of Decarburisation

Decarburisation may occur in either reducing or oxidising atmospheres.

In oxidising atmospheres, other defects arise as a result of the penetration of oxygen into the hot steel. Oxygen initially penetrates along the grain boundaries in solid solution in the form of ferrous oxide in ferrite, formed by inward diffusion of oxygen along the austenite grain boundaries. This product is known as the relief constituent; it has a light colour which can easily be recognised during a microscopic examination. Being hard and brittle it is a source of weakness.

As the penetration of oxygen continues, the bands of relief constituent increase until a precipitate appears, in the form of globules, along the centre of the ferrite network. This precipitate continues a source of weakness, acting as a stress concentrator in the material. Silicate and nitride inclusions, if present in the zone of a stress concentration, are also particularly harmful.

The mechanism of decarburisation consists of three separate processes:

1. carbon loss;
2. appearance of the relief constituent;
3. oxygen penetration.

However, these processes occur almost simultaneously and vary in severity according to the composition and structure of the steel in question. The rate of decarburisation is generally governed by Fick's law of diffusion:

$$\frac{dc}{dt} = \frac{d}{dx}\left(D\frac{dc}{dx}\right)$$

where D = diffusion coefficient of the metal.

dt = time interval.

$\frac{dc}{dx}$ = concentration gradient.

Hence it can be shown that the higher the concentration gradient, the more quickly the carbon will diffuse from the centre of the metal to the decarburised outer layers, thus tending to restore some of the lost carbon and reduce the extent of decarburisation.

Ball(1) established that silicon-manganese steel is more prone to surface decarburisation than plain carbon steel. He also found that, as oxidation proceeds silica is always formed in advance of the iron oxide relief constituent.

Hendy(2) suggested that full depth of oxygen penetration may not be visible under the microscope, as the apparent depth is slightly less than that at which a decrease in fatigue strength occurs.

That this loss in fatigue strength is due to the notch effect of oxygen penetration rather than carbon loss was verified experimentally by Watkinson(3) and by others,(4, 5, 6).

On the basis of his experimental work, Watkinson(3) concluded that fatigue strength is continuously reduced as the degree of decarburisation increases, until a completely ferritic surface is produced. These findings were confirmed by Simovich and Loria,(7) who found that for axial stresses, especially in the high stress range the fatigue strength decreased with the increasing depth of the decarburised layer. The depth of decarburisation (for methods of measurement see Appendix) and degree of oxidation depend to a critical extent on the heating atmosphere, temperature and time(6). Efforts have been made to determine the optimum conditions for minimising these effects,(8, 9, 10, 11).

2. MATERIAL

Of the steels exployed in the spring industry, a Si-Mn steel was selected for the investigation, since it is known to be susceptible to decarburisation. The base material was in the form of rod, having a nominal composition (weight %) of:

C	Si	Mn	S	P
.50/.60	1.5/2.0	0.7/1.0	0.05 max	0.05 max

3. EXPERIMENTAL PROCEDURE

3.1. Heat Treatment

The fatigue specimens, as shown in Fig. 1, were initially machined to 0.38 mm oversize. Specimens which were to have a decarburised layer were machined 0.05 mm oversize, so that the decarburised layer would decrease by a only small amount prior to fatigue testing. The remaining specimens, which were to be tested without any decarburisation, were heat-treated whilst still 0.38 mm oversize, so that any decarburisation occurring spontaneously during heat-treatment could be removed before the fatigue testing was carried out.

By evaluating various heat-treatments, it was found that heat-treatment in a non-scaling atmosphere at 950°C for 15 minutes produced a specimen having a decarburised layer of about 0.51 mm. Since heat-treatment time must be quadrupled to double the depth of decarburisation, it was decided to treat one batch of specimens for one hour and a further batch for three hours.

The specimens were quenched in whale oil to 60°C and tempered for one hour at 430°C.

The group of non-decarburised specimens was heat-treated for 20 minutes and then subjected to the same quenching and tempering treatment as the other groups.

The average depth of decarburisation was determined, for ease of measurement, on photomicrographs of fatigued and then normalised specimens. The values obtained were: 0, 0.13, 0.51 and 0.84 mm respectively according to the austenitisation times.

3.2. Fatigue Testing

The specimens, grouped A to D according to the degree of decarburisation, were subjected to rotating-bending fatigue tests at stress levels ranging from 250 to 750 N/mm^2 and the number of cycles to failure was recorded. The stress levels and number of cycles at which failure did not occur within 100 hours were also recorded.

4. EXPERIMENTAL RESULTS

The fatigue data for the various groups of decarburised specimens are shown in Table 1.

The fatigue strengths for each group were determined from the stress amplitude/cycles to failure curves in Fig. 2. The fatigue strengths at an endurance of 10^6 cycles were plotted against the depth of decarburisation for each group of specimens, as shown in Fig. 3.

5. DISCUSSION

The general trend of the results showing the deleterious influence of decarburisation on fatigue strength is as expected. However, the quantified, non-linear decrease in fatigue strength with increasing depth of decarburisation, as shown in Fig. 3, is a finding of great significance for the spring industry. A 25% reduction in fatigue strength can be attributed to a decarburisation depth of as little as 0.13 mm. Increasing decarburisation beyond this level produces a significant, though less substantial, reduction in fatigue strength. It is therefore of importance to establish the optimum method of preventing decarburisation for use under production conditions.

Techniques have been considered for preventing decarburisation, not only in Si-Mn steels but also in other materials generally employed in the spring industry.

Probably the most satisfactory and, in the long term, the cheapest method is careful control of furnace atmosphere. The choice of furnace atmosphere generally depends upon the type of process employed, the availability of the source material, the degree of control required and the cost.

A summary of the more important atmospheres available commercially(12-24) is given in Table II.

The ideal atmosphere is one which remains completely inert during the heating, soaking and cooling phases of the cycle. In many cases this is not practicable and the choice of atmosphere can only be made after detailed consideration of the metal composition and temperature cycle.

Undried, rich exothermic gas prevents oxidation of plain carbon and low alloy steels using normal cycles but has a significant decarburising effect on steels of above about 0.2% carbon(12). To eliminate decarburisation completely with high-carbon steels, nitrogen or dried, stripped, exothermic gas or endothermic gas with hydrocarbon additions must be used(14, 15, 17, 22).

With higher alloy steels, especially those containing elements which have a great affinity for oxygen, the presence of any oxygen-bearing gases is deleterious. Stainless steels, for example, require pure dry hydrogen(21) or cracked ammonia(18) to produce really bright results from the annealing process; dried, stripped exothermic gas which is occasionally used, gives a slightly oxidised finish(15). Recently, vacuum heat treatment has been used for high-carbon steel wire; this gives a bright finish with complete freedom from decarburisation. Protective coatings are also used in an attempt to eliminate decarburisation. Although complete success may be obtained with the expensive aluminising and chromising methods(25), the boric oxide treatments are less successful. Moreover, the boric oxide solvents, which are generally toxic and/or inflammable, constitute a health hazard.

6. CONCLUSIONS

1. Decarburisation has a serious detrimental effect on the fatigue strength of hardened and tempered Si-Mn spring steel. Only a small depth of decarburisation is required to produce the maximum effect on the reduction of the fatigue strength.

2. Decarburisation may be eliminated by the careful control of furnace atmosphere and some degree of success in eliminating decarburisation can be achieved by the use of surface coatings.

7. FUTURE WORK

The influence of decarburisation on the fatigue properties should be quantified by producing a number of fatigue strength/decarburisation depth curves for various spring steels.

The cost-effectiveness of controlled furnace atmospheres may be examined in detail, to provide the manufacturer with a guide to the financial aspects of their use.

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11. APPENDIX

11.1. The Measurement of Decarburisation

The depth of decarburisation can be defined in different ways as the effect decreases in intensity toward the centre of the specimen. It is very difficult to pinpoint a precise boundary line for measurement purposes: is the extent of decarburisation taken to be the depth at which there is no loss in carbon percentage or the depth at which there is very little percentage loss of carbon? Accuracy in assessing decarburisation by conventional metallographic methods is therefore largely dependent upon the skill of the metallographer.

It is common practice to use an apparent decarburisation boundary that is easy to measure; if possible, however, it is preferable to choose a decarburisation boundary with the function and performance of the final component in mind.

The main methods of detecting decarburisation are:

1. Microscopic examination of a specimen mounted in such a way that the decarburised edge is preserved.
2. Measuring the loss of weight of the specimen.
3. Etching the specimen, which can show the decarburised layer lighter in colour than the core.

Once the presence of decarburisation has been detected, measurement of its depth is usually required. Four main methods may be employed, all of which have advantages and disadvantages. The methods are:

a. Analysis of the surface layers for carbon

This method of turning bars of circular cross-section in a lathe to a measured depth and collecting the turnings for analysis. The main advantages are the accuracy of the results obtained and the clear indication of different degrees of decarburisation at the different depths. Unfortunately, the method is time-consuming and hence costly.

Furthermore it can not be used for a specimen of irregular shape or for materials too hard to machine.

b. Measurement of loss of weight

This method gives a good indication of the degree of decarburisation and is far quicker than method (a), but it cannot be used in cases where an oxidising atmosphere has caused scaling and does not indicate the nature of the carbon gradient throughout the specimen.

c. Hardness Tests

These show the presence of a soft layer but do not indicate its depth accurately. Accurate measurements can be made by grinding a sloping section through the surface of the specimen so that the distance between the hardness impressions along the surface represents a fractional advance into the depth of the specimen. This is a reasonably quick method but can only be applied to specially prepared specimens and hardness values may be affected by any change in gain size or slight variations in the technique of preparing the surface. Any error resulting from grain-size can be largely removed by quenching. The method is not practicable for irregular structures.

d. Microstructure

Decarburisation produces changes in the microstructure and this can be shown by using a polished and etched specimen which has been cut at right angles through the decarburised layer. The sloping section for the hardness tests can also be used for microexamination. To determine the actual depth of structure transformed by decarburisation, it is necessary to measure the quantity of ferrite present at different depths. A technique has been developed whereby the structure is photographed at a certain magnification and projected on to a screen ruled with parallel lines of a defined width. The projector is adjusted so that this corresponds to a fixed distance on the specimen. The amount of ferrite covering each line is then measured and expressed as a percentage of the total structure on the line. This method may be used for specimens of any shape but the inaccuracy increases as the fineness of the structure increases and results vary where the basic structure is ferrite and pearlite.

These four methods are still the most widely used today although research is continuing into the use of complex electrical equipment to measure the depth of decarburisation, e.g. Nuriev(1) is investigating the use of electromagnetic methods and is employing a multi-parameter eddy-current method in an attempt to eliminate the interfering factors. Bramhall(2) is experimenting with a spectrographic method of measuring decarburisation, utilising the fact that vacuum direct reading emission spectometry provides a versatile and accurate technique for the determination of carbon gradients in steel.

11.2. References

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TABLE I FATIGUE DATA FOR DECARBURISED Si-Mn SPRING STEEL

GROUP	SPECIMEN IDENTIFICATION	STRESS AMPLITUDE N/mm^2.	CYCLES TO FAILURE
			NUMBER
A (O decarb.)	1	710	3.66×10^6
	2	755	8.8×10^4
	3	740	1.32×10^6
	4	725	2.15×10^6
	5	710	4.75×10^6
		695	U/B 1.27×10^7
B (0.13 mm decarb.)	1	585	7.8×10^4
	2	510	3.07×10^6
	3	525	1.45×10^6
		500	U/B 1.32×10^7
C (0.61 mm decarb.)	1	465	9.02×10^4
	2	400	4.51×10^5
	3	385	9.24×10^5
		370	U/B 1.5×10^7
D (0.84 mm decarb.)	1	450	1.1×10^5
	2	400	2.8×10^5
	3	370	5.7×10^5
	4	245	3.08×10^5
	5	310	1.62×10^6

U/B - Unbroken

TABLE II (a) INDUSTRIAL CONTROLLED ATMOSPHERES

ATMOSPHERE	TYPICAL USES	METALS	ADVANTAGES	DISADVANTAGES	REFERENCE
Rich Exothermic	Normalising	Ferrous	Cheap	Can cause decarburisation and sooting	12
Lean Exothermic	Bright annealing	Copper, nickel, aluminium, brasses	Cheap Non-explosive	Sulphur removal required	13
Rich Stripped Exothermic	Hardening	Ferrous	Relatively cheap Non-decarburising	Can cause sooting	14
Lean Stripped Exothermic	Annealing	Ferrous	Non-decarburising	Can cause sooting	15
Modified Stripped Exothermic	Long-cycle	Low carbon	Non-sooting	-	16
Endothermic	Hardening	Ferrous	Non-decarburising	Explosive; Can cause sooting; Good control necessary	17

TABLE II (b) INDUSTRIAL CONTROLLED ATMOSPHERES

ATMOSPHERE	TYPICAL USES	METALS	ADVANTAGES	DISADVANTAGES	REFERENCE
Cracked Ammonia	Bright annealing	Stainless steels, Copper & nickel alloys	Pure	Can cause nitriding effects	18
Partially Burned Ammonia	Bright annealing	Stainless steels, copper & nickel alloys	Cheaper than cracked ammonia	-	19
Fully Burned Ammonia	Special annealing & hardening	Special non-ferrous metals & steels	Non-explosive	-	20
Hydrogen as for Cracked Ammonia				Expensive; Explosive	21
Nitrogen as for Cracked Ammonia			Non-explosive; inert; little capital needed	Expensive	22
Argon	Bright annealing special components	Titanium; Nimonics; Special steels	Non-explosive; inert; little capital needed	Very expensive	23
Steam	Tempering; Bright annealing	Steel; Copper	Very cheap; non-explosive	Condensate difficulties	24

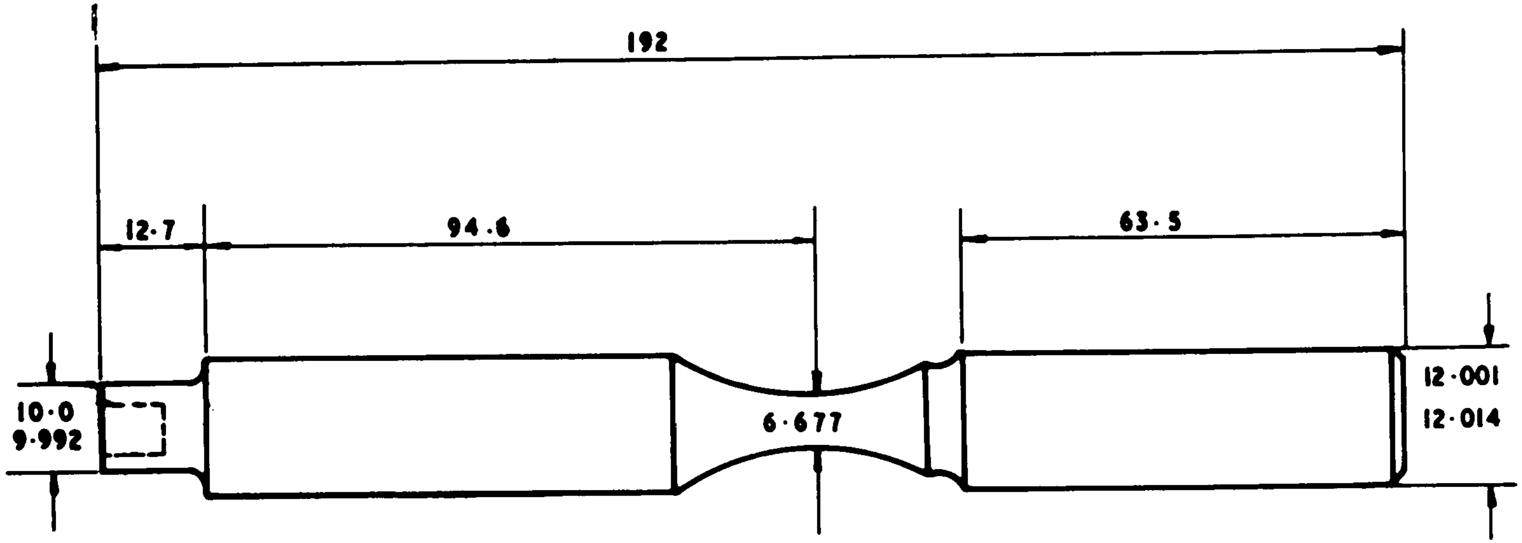

FIG. 1 DESIGN OF FATIGUE SPECIMEN. (mm)

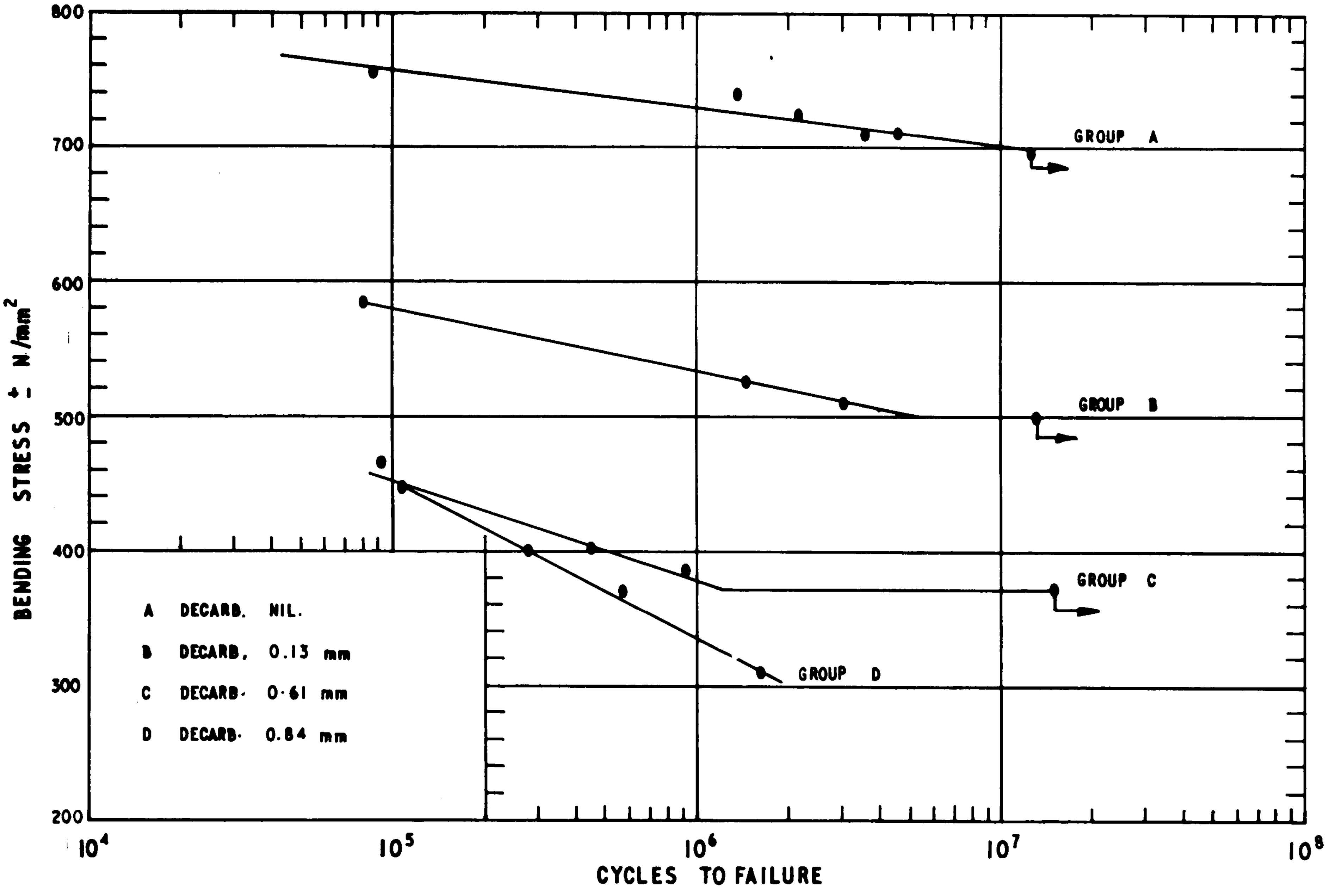

FIG. 2 FATIGUE CURVES FOR DECARBURISED Si-Mn STEEL.

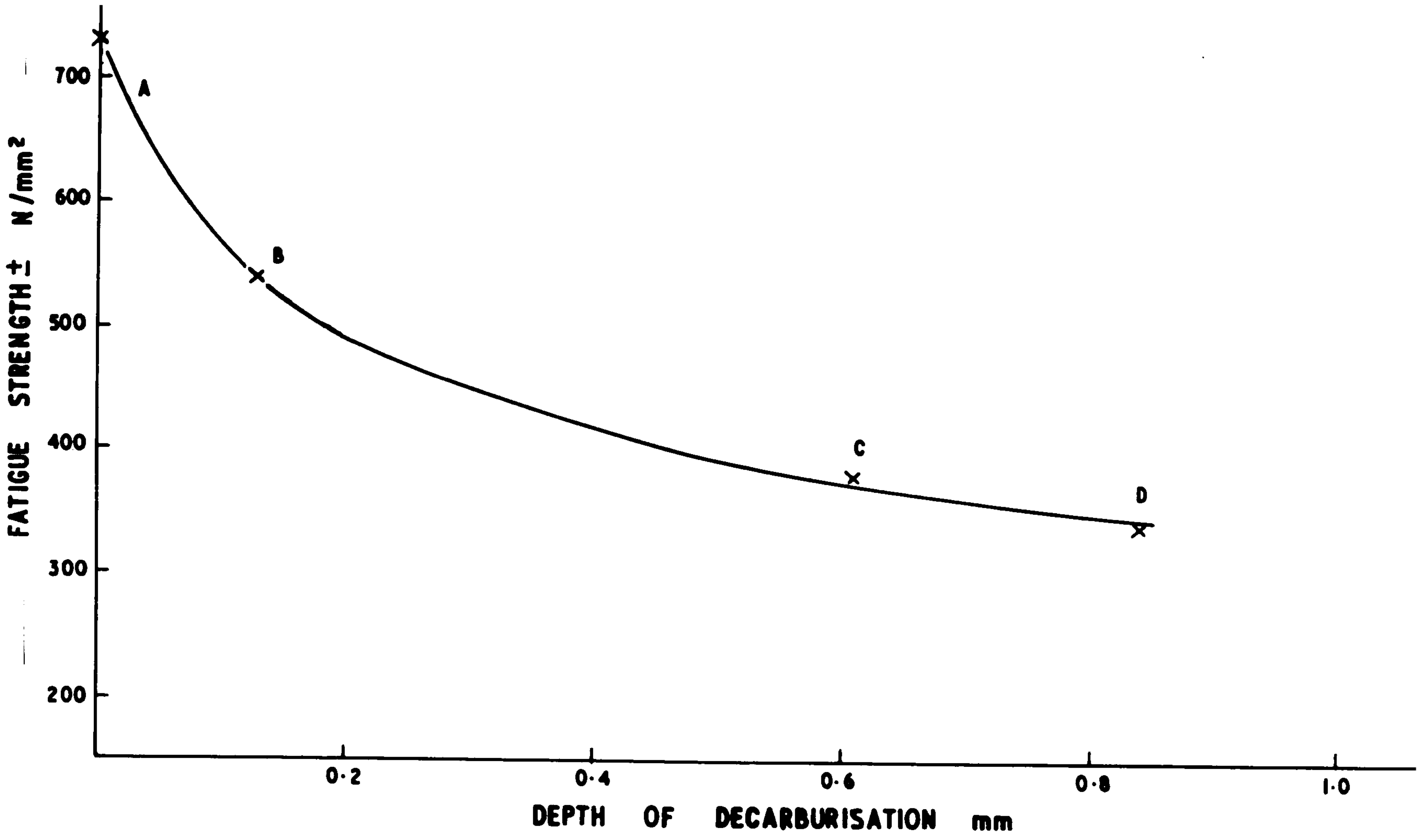

FIG. 3 EFFECT OF DECARBURISATION ON FATIGUE STRENGTH AT 10^6 CYCLES.