SPRING MANUFACTURERS' RESEARCH ASSOCIATION

The Effect of Carbon Restoration and Shot-Peening on the Fatigue Strength of Highly Stressed Heavy Coiled Compression Springs

Report No. 135

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NOTE:

This paper was presented at a private conference held at Harrogate and organised by the Spring Manufacturers' Research Association. It was attended by delegates from the French, German, Italian, U.S.A. and U.K. spring industries.

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THE EFFECT OF CARBON RESTORATION AND SHOT-PEENING ON THE FATIGUE STRENGTH OF HIGHLY STRESSED HEAVY COILED COMPRESSION SPRINGS.

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1. GENERAL INTRODUCTION

The majority of hot-coiled heavy springs are made from silicon-manganese or high carbon steels. The bars as rolled or in the ground condition are heated for coiling at 850° - 1,000°C for 20 - 30 minutes in atmospheres which are often oxidising so that the steel is decarburised and scaled to some extent. The bar is then coiled on a mandrel when the majority of the scale flakes off. The formed spring may be quenched directly from the mandrel or allowed to cool to room temperature before reheating for quenching. In either case the spring will have an oxidised surface.

Oxidation of steel at these temperatures results not only in loss of carbon but, increasingly at temperatures above 900°C, oxygen penetrates along the austenitic grain boundaries resulting in the formation of oxide filaments or a solid solution of FeO which appears microscopically as a relief constituent. (Fig. 1) It has been shown that although in the polished condition spring steels can have an endurance limit in repeated torsion of approximately 50 - 55 ton/sq.in. rising to over 60 ton/sq.in. after shot peening, in practice decarburisation reduces these values significantly. It has also been shown that shot-peening produces compressive stresses in the surface which counteract the effect of the tensile stresses which initiate fatigue failure, but as the severity of decarburisation increases, so the extent to which the resolved tensile stresses are offset by residual compressive stresses falls and this is in addition to the fact that the fatigue strength of the ferrite layer is less than that of the carbon steel core.

On the other hand, when carbon is restored to decarburised surfaces the compressive stresses developed by peening are normally sufficient to transfer the point of failure to a position below the surface and the fatigue strength is then approximately equal to that achieved in polished shot-peened specimens.

These significant facts, established in laboratory tests [1,2,3] indicated the conditions under which shot-peening could be used to advantage.

To test the validity of the laboratory results springs were made in order to study variation in composition, surface condition, and surface treatment on the fatigue properties.

2. PROCEDURE

The following factors were investigated:

(i) The effects of surface treatment on the fatigue strength of springs; manufactured from 3 steels in both black and ground bar and coiled at
   (a) 900°C and reheated to 900°C for quenching
   (b) 950°C and quenched direct from the mandrel
   (c) 1,000°C and quenched direct from the mandrel

(ii) The effects of shot-peening on the fatigue strength of the springs in (i)

(iii) The effects of reheating to 900°C in a gaseous carburising atmosphere for quenching followed by shot-peening, on the fatigue strength of the springs in (i)

The flowsheet for spring manufacture is detailed in Fig.2.

The compositions of the steels were

Steel	C%	Si%	Mn%	S%	P%	Cr%	Ni%
A(EN.45)	.57	2.02	1.05	.045	.040	.03	.10
B(EN.44)	1.01	.17	.66	.047	.030	.06	.10
C(EN.42)	.78	.17	.77	.048	.037	.06	.08

and the material was prepared and supplied to STA.2

The spring design was:

Bar diameter	=	1.04 in.
Mean coil diameter	=	3.5 in.
Free height	=	20.28 in.
Solid height	=	15.08 in.
Solid stress (corrected)	=	80 ton/sq.in.
Number of effective coils	=	13.5

3. EXPERIMENTAL METHODS

3.1 Shot Peening

The methods at present in use employ either an air blast or a mechanical impeller for projecting the shot. Standard specifications exist for shot over a large range of sizes and attempts have been made to devise reliable methods for the quantitative measurement and control of the process. The most commonly used method of control has been that of Almen who utilised the measurement of curvature of small strip specimens.

The conditions of peening in the present work were the same as used by Watkinson(1) viz:

1/32 in. round chilled iron shot
nozzle 3/8 in. diameter
Pressure 30 lb/sq.in.

distance of nozzle to job 6"
coverage of peening 4 sec/sq.in.

3.2 Carbon Restoration

Carbon restoration was carried out in an atmosphere of endothermic gas enriched with butane in a sealed quench furnace, a diagram and photograph of which are shown in Fig.3.

Micro-examination and measurement of depth of decarburisation of control samples indicated the required carburising and diffusion times for carbon restoration. The springs were lightly grit blasted to remove scale prior to the treatment. The carburising times varied from 20-45 min. after which diffusion was carried out to a total treatment time of 1 hour.

3.3 Fatigue testing

S-N curves were determined on two machines, one of which is shown in Fig.4. Testing was continued until failure or until a life of 500,000 cycles was achieved whichever was the sooner.

4. EXAMINATION OF SPRINGS AFTER TESTING

The fractures of all broken springs were examined visually to determine the origin and type of failure and it was found that 69 springs in silicon-manganese steel (62 from black bar); 11 springs of high carbon steel, (8 from black bar); 18 springs of medium carbon steel (12 from black bar) failed due to surface defects.

Metallurgical examination was carried out on at least one unbroken and three broken springs from each batch and also on springs having a fatigue life far removed from the S-N curve. The depths of complete and partial decarburisation and the quality of recarburisation were measured on sections of the springs after normalising. Hardness tests were taken across the section and additionally on the surface and on tapered sections to determine the effect of shot peening on hardness.

4.1 Structure

Through hardening was achieved in the silicon-manganese steel (Steel A). The high carbon steel (Steel B) was martensitic to a depth of .050" below which was an intermediate transformation product. The medium carbon steel (Steel C) had a completely tempered martensitic structure in all but a few cases.

4.2 Decarburisation

Depths of decarburisation are shown in Figs. 5, 6 and 7. Silicon-manganese (Steel A) - total depth of decarburisation varied from 0.024 in. to 0.036 in. in black bar and 0.015 in. to 0.020 in. in ground bar. High carbon steel (Steel B) - decarburised to 0.010 to 0.011 in. in black bar and 0.005 in. to 0.009 in. in ground bar.

Medium carbon steel (Steel C)- decarburised to 0.014 in. to 0.018 in. in black bar and 0.009 in. to 0.014 in. in ground bar.

In each steel the depth of decarburisation increased with an increase in the coiling temperature and almost completely ferritic surfa were found in the springs of Steel A coiled from the highest temperatur

4.3 Recarburisation

Restoration of the carbon in the most heavily decarburised black bar material was not complete, some slight decarburisation remained on the inside of the coils at depths varying from .006 in. to .016 in. below the surface. Carbon restoration of ground bar springs was complete for Steel C coiled from 900°C and 1,000°C and almost complete in all other batches.

4.4 Spring Hardness

Internal

There was a wide variation in hardness between springs of each batch and each manufacturer. Of the springs which were not recarburised those which had been quenched direct from mandrel showed the greater variation in hardness. The hardness of each batch of recarburised springs was more uniform, indicating the effect of a scale free surface on quenching efficiency. The ranges of hardness for the various surface conditions are shown in Fig.8.

Surface

The silicon-manganese steel was decarburised more severely resulting in a greater reduction in hardness near the surface than was the case with the carbon steels

5. RESULTS

5.1 General

Three factors other than mechanical defects control the fatigue strength of heat treated and shot peened surfaces:

(i) The fatigue strength of the steel in the heat treated condition.

(ii) The depth and severity of decarburisation.

(iii) The magnitude of the compressive stresses produced in the surface by shot peening.

The fatigue test results are presented in Table I.

Shot peening of black bar springs did not always produce an improvement in fatigue properties.

Shot-peening of ground bar springs gave a more regular improvement.

Carbon restoration followed by shot peening resulted in a marked improvement in the fatigue properties of springs made from both black and ground bar. Where carbon restoration was complete the fatigue properties approached those obtainable earlier on laboratory test specimens.

DISCUSSION

The relative merits of quenching from the mandrel or re-heating for quenching have long been argued. Hardening may be more easily accomplished in the former since the scale formed on heating flakes off during coiling and the springs do not suffer from the insulating effects of the scale during quenching. Reheating the coiled bars for quenching (4) not only increases the extent and severity of decarburisation but further scale forms which markedly reduces the efficiency of the quench. On the other hand, so that the springs retain sufficient heat after coiling to be efficiently hardened, the bars must be heated initially to high temperatures, i.e. 950°C to 1,050°C at which temperatures the spring is exposed to the oxidising action of air. Decarburisation and oxidation occur at this stage. When reheating for quenching this initial margin of temperature is not required and the bars need not be heated above 900°C. Moreover when the methods employed include carbon restoration which involves removal of the scale and also re-heating for quenching in a carburising atmosphere the adverse effects previously associated with this treatment do not occur.

Coiling from 950°C and 1,000°C produced greater depths and severity of decarburisation in each of the three compositions of steel, more particularly the springs manufactured from silicon-manganese steel which is more prone to decarburisation. The ferritic surfaces produced reduced the work hardening capacity and therefore the magnitude of the compressive stresses produced by peening.

The improvement in fatigue properties due to peening springs made from black bar was irregular and sometimes non-existent in the as-heat treated condition. Where ground bar was used decarburisation was not so severe and improvements effected by shot peening were more regular.

The fatigue properties obtained for the three different steels in the carbon restored and shot peened condition are similar, provided results due to rolling defects are ignored. The results for the medium carbon steel C compare well with those for the silicon-manganese Steel A. The silicon-manganese steel does not exhibit fatigue properties superior to those of the other steels, even when due allowance is made for the effect of seams and other rolling defects. In practice of course the influence of these defects to which Si-Mn steel is particularly prone cannot be ignored. The great advantage of Si-Mn material is its hardenability but when carbon restoration was employed as part of the process, all the steels investigated hardened efficiently.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 With the particular shot-peening conditions employed, there was little benefit from shot-peening springs manufactured from black or ground bar which were to be used in the "as heat-treated condition".

7.2 Carbon steel springs made from black bar with a double treatment involving carbon restoration followed by shot peening gave better fatigue properties than ground bar single or double heat treated and shot peened.

7.3 Notches and seams sometimes gave rise to early fatigue failures irrespective of whether the springs had been shot peened or carbon restored and shot peened.

7.4 Certain manufacturing procedures may be proposed on the basis of the improved fatigue properties obtained on the carbon-restored and shot-peened springs. Such recommendations are fully justified by the close connection between the actual properties obtained on the springs and the laboratory results obtained on straight bar specimens made under similar conditions. The desirable features of springs which are to withstand indefinitely stress ranges of 50-55 tons/sq.in. are:-

(a) Absence of causes of stress-concentrations.

(b) Complete absence of decarburisation in the finished spring so that the maximum effect of shot peening can be obtained.

(c) Satisfactory hardening.

These requirements are substantially met if ground bars are used and heated for coiling at a temperature preferably not exceeding 900°C. The springs should be allowed to cool and re-heated for quenching in a carbon restoration furnace whose carbon potential is slightly greater than the carbon content of the steel. When restoration of carbon is complete the springs should be quenched and tempered prior to shot peening.

8. REFERENCES

1. J. Watkinson - Ph.D. Thesis University of Sheffield 1954.

2. J. Watkinson - Influence of Some Surface Factors on the Torsional Fatigue Strength of Spring Steels. Inst. Mech. Engineers. International Conference on Fatigue 1956.

3. J.O. Almen - Shot Peening. 1959 sixth edition. P 131 - 147 (Wheelabrator Co. Indiana, U.S.A.)

4. J.W. Mee - C.S.F.R.O. Report No. 101.

COMMENTS OF THE SPRING MANUFACTURERS' RESEARCH ASSOCIATION ARISING FROM THE RESEARCH

1. The improvement in fatigue properties due to shot-peening without recarburisation was smaller than was expected in the light of industrial experience. This was due at least in part to the shot-peening conditions employed, which, for the purpose of continuity, were identical with those used in the earlier laboratory research. It is now well known that cut wire and steel shot are superior to chilled iron and would be expected to produce a greater improvement in fatigue properties. However, considering the relatively low cost of the shot-peening process, even the small gains shown in this research would be economically worthwhile for many applications.

2. The results presented are based on one cast of steel in each of the three chosen B.S. compositions and it is recommended that further research be carried out on a narrower front, using steels of different cast analyses, to evaluate further the effect of recarburisation in conjunction with a more rigorous shot-peening treatment, on the fatigue properties of the different spring steel qualities.

DISCUSSION

MR. COLE Could the speaker explain the method used to determine the intensity of shot peening, and could he give a figure for this intensity.

MR. MEE The Almen strip was used to measure intensity. No tests were taken whilst the springs were actually being peened. The conditions were established beforehand such that the coverage was four seconds per square inch.

HERR WATERSTRADT In the paper you say the springs were tested for a life of 500,000 cycles. Can this be taken as the endurance limit?

MR. MEE The springs were tested at 140 cycles per minute and the tests were discontinued at 500,000 cycles. We realise that the fatigue strength at 500,000 cycles may not be the same as the fatigue limit. This type of spring is replaced on a maintenance programme and 500,000 cycles would be a practical limit.

MR. HAYNES When determining the endurance limit it is customary in this country to obtain two unbroken points but as these tests were only continued to 500,000 cycles you will appreciate it was often impossible to do this, therefore, the stress values quoted are in effect fatigue strengths and not fatigue limits. The terms of the contract limited the testing to 500,000 cycles.

M. CATTIER I have three questions to ask. We are surprised that the limits of fatigue were only determined for carbon steel and manganese steel, was the same hardness used for the two qualities of steel?
The second point, you have not compared the fatigue properties of the carbon restored shot peened springs with those of carbon restored springs not shot peened. Is it less important to shot peen carbon restored springs?
Thirdly, what practical applications do you envisage from the results of your research?

MR. MEE In reply to your first question, three steels were used which are in common use in the British Spring Industry, other alloy steels are also used for springs, but to keep the research in reasonable proportions only the three common steels were studied.

MR. SOMERTON The optimum hardness of the silicon-manganese steel was in the region of 515 HV. For the carbon steels the hardness lay between 440 to 480 HV. The hardness of the medium carbon steel was 440 HV.

MR. MEE One point which has not been determined is the increase in life due to carbon restoration alone. It is therefore difficult to say what proportion of the increase in life was due to carbon restoration or shot peening. The third point raised by M. Cattier was the practical application of the research. For this type of spring any decrease in weight would result in decrease in weight of the spring seating and consequently of the vehicle.

DR. BENHAM I would like to take up this point about the endurance life to which these tests were run. With regard to this endurance of 500,000 cycles Mr. Haynes said that this may well be close to the knee of the S-N curve. We have done some tests at Imperial College on the effects of carbon restoration but not in conjunction with shot peening. The results showed that the fatigue strength was considerably raised by carbon restoration, but that there was no apparent fatigue limit for the specimens. Our tests were continued to 50 million cycles. I am not suggesting that these tests are exactly comparable with those of Mr. Mee's but I would like to have seen his tests continued to a longer life to establish that (a) there was a true fatigue limit and (b) if the knee of the carbon restored curve was moved to the right, and whether the difference between the non-restored curve and the carbon restored curve was as much as was given in the paper.

MR. HAYNES There is one fundamental difference between the tests carried out by Dr. Benham and those referred to in this paper, the difference being the steel composition. The Imperial College specimens were made from EN.36 which was case carburized not carbon restored. The springs used in our laboratories were made from fairly high carbon steel and the carbon restoration treatment was used only to put back carbon which had been lost.

I think therefore that the difference in the results obtained in this paper and those at Imperial College might be explained by the different metallurgical treatments. Regarding Dr. Benham's suggestion that the tests should run on for 10 million cycles, I too would like to see this, but as you will appreciate this work was limited by the contract in order to obtain the results in a reasonable space of time.

MR. STEELE May I come back to this question of hardness and ask if Fig. 8 refers only to the hardness of silicon-manganese, or is the shaded area indicative of the spread in hardness for the three steel qualities investigated.

MR. MEE Fig. 8 includes all hardness values taken on the three qualities of steel and is intended to show the variation in hardness for unpeened, shot peened and carbon restored and shot peened springs. That is why the scatter bands are so wide.

MR. HAYNES If the scatter bands for each steel had been shown separately they would have in fact overlapped, and the difference between them would not have been significant.

HERR [illegible]REINBERG The amount of decarburisation seems to be rather large and we can only conclude that this arose during rolling. Secondly, the spring failures would appear to be surface failures and we can only conclude that this research was an investigation into the effects of surface on fatigue. We have a maxim in the German spring industry which says "all good springs are made in the rolling mill".

My third question deals with the control of carbon restoration. We have done some experiments in Germany and have shown that the carbon restoration period will depend on the amount of decarburisation present in the springs.

I would be interested to know what control there was in this case.

MR. MEE Dealing with the first point 'where the decarburization came from'; in the case of the ground bars there was no decarburization prior to spring making.

On the black bars decarburization varied between 0.005 to 0.010". The remainder of the decarburization found in the finished springs was formed during heating for spring coiling and/or heating for quenching. On the second point it is true that failure started from the surface, consequently the surface condition played an important part in the life of the springs. With regard to the control of carbon restoration the restoring period varied from 20 to 40 minutes, and the rest of the time (to a total time of 60 minutes) was used for carbon diffusion. It may well be that with 45 minutes of carbon restoration a longer diffusion time would have been better. From a production point of view, where the decarburization is likely to vary there may be difficulties in deciding on the most suitable carbon restoration treatment.

MR. JOBLING It is true that in this case the carbon restoration was carried out in a small batch type furnace and from the point of view of the heavy spring industry this could only be considered as an experiment. In the automotive industry large continuous carburising furnaces are used which might well be suitable for carbon restoration of springs on a mass production scale. It was mentioned in the report that the carbon potential was a little higher than that required by the steel and the restoration treatment divided into carbon restoration and diffusion. In the case of silicon-manganese it is not possible to over carbon restore, therefore, with a steel of this composition the process can be simplified to a straightforward carbon restoration period with no diffusion.

MR. [illegible] CLARK Could Mr. Mee enlighten me on the term "Walterising"?

MR. MEE "Walterising" is a trade name for a hot phosphating treatment.

HERR WALTERSTRADT In Table 1 stress values are quoted and I should be pleased to know whether these are the maximum stress values. I should also like to know what were the minimum stresses on the springs so I could calculate the stress range imposed during testing.

MR. MEE The values quoted are for maximum stress. The initial stress used on all tests was 5 tons/sq.in., this was just sufficient to operate the cut-out mechanism on the testing machine when a spring failed or set down.

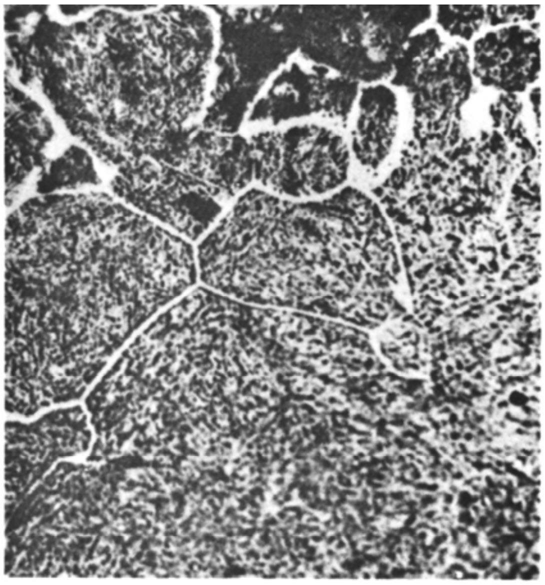
DR. GENDERS For the benefit of our visitors I would like to explain the background of this work. This paper represents the testing of conclusions obtained from earlier research work carried out for a number of years.

When the research organisation was first formed, a research programme was drawn up in collaboration with our members and it became clear that two problems were of general interest. Whether either the single or double heat treatment of coiled springs was better from the point of view of spring properties. Metallurgically we said, of course, that the double treatment was superior. We carried out some initial tests and it became clear that there was no rapid answer to the problem. There is one particular point which has always worried me, that is, once a steel is decarburized we have thought that the damage to the surface of the steel could not be completely repaired by adding carbon because of the presence of grain boundary oxide penetration which has a weakening effect.

The other point which came into our original programme was the carbon content of the steel. As metallurgists we could not quite understand why spring makers made their springs of a 1% carbon steel. It is well known that if the carbon content varies from that of eutectoid (0.8%) difficulties may arise in obtaining satisfactory hardening, and so far as they go I think the results substantiate this idea.

TABLE I EFFECT OF CARBON RESTORATION AND SHOT PEENING ON FATIGUE PROPERTIES

Steel	Coiling Temp. °C	Decarburised Springs				Carbon restored & shot peened springs	
		Depth of 50% ferrite (in)	Total affected depth (in)	Stress for 0.5 x 10^6 cycles (ton/sq.in.)		Decarburisation	Stress for 0.5x10^6 cycles (ton/sq.in.)
				Unpeened	Shot peened		
A Black Bar	900	.007 - .010	.019 - .024	42.5	42.5	Nil	49.0
	950	.010 - .018	.022 - .036	37.5	41.0	Nil	45.0
	1000	.014 - .019	.025 - .032	37.5	42.5	Nil	53.0
A Ground Bar	900	.006 - .007	.013 - .017	50.0	52.0	Nil	55.0
	950	.007 - .009	.012 - .015	44.0	46.5	Slight at .016 in.	53.0
	1000	.008 - .010	.015 - .020	42.5	46.0	Nil	60.5
B Black Bar	900	.003 - .005	.007 - .010	47.5	49.0	Slight at .006 in.	52.0
	950	.003 - .005	.006 - .010	44.0	44.0	Slight at .006 in.	50.0
	1000	.004 - .006	.009 - .011	39.0	44.0	Slight at .007 in.	46.5
B Ground Bar	900	Nil - .002	.004 - .005	46.0	48.5	Nil	53.0
	950	.001 - .004	.004 - .006	42.5	45.0	Slight at .007 in.	53.0
	1000	.003 - .004	.006 - .009	43.5	43.5	Slight at .008 in.	51.0
C Black Bar	900	.004 - .006	.011 - .014	42.5	48.5	Nil	53.0
	950	.003 - .006	.012 - .015	43.0	43.0	Slight at .014 in.	51.0
	1000	.006 - .009	.014 - .018	41.5	41.5	Slight at .012 in.	50.5
C Ground Bar	900	Nil - .004	.008 - .011	47.5	51.5	Nil	56.0
	950	Nil - .003	.006 - .009	44.0	44.0	Nil	53.0
	1000	.001 - .005	.006 - .014	41.0	45.0	Nil	53.0



X 500

FIG. 1 RELIEF CONSTITUENT IN MEDIUM CARBON STEEL

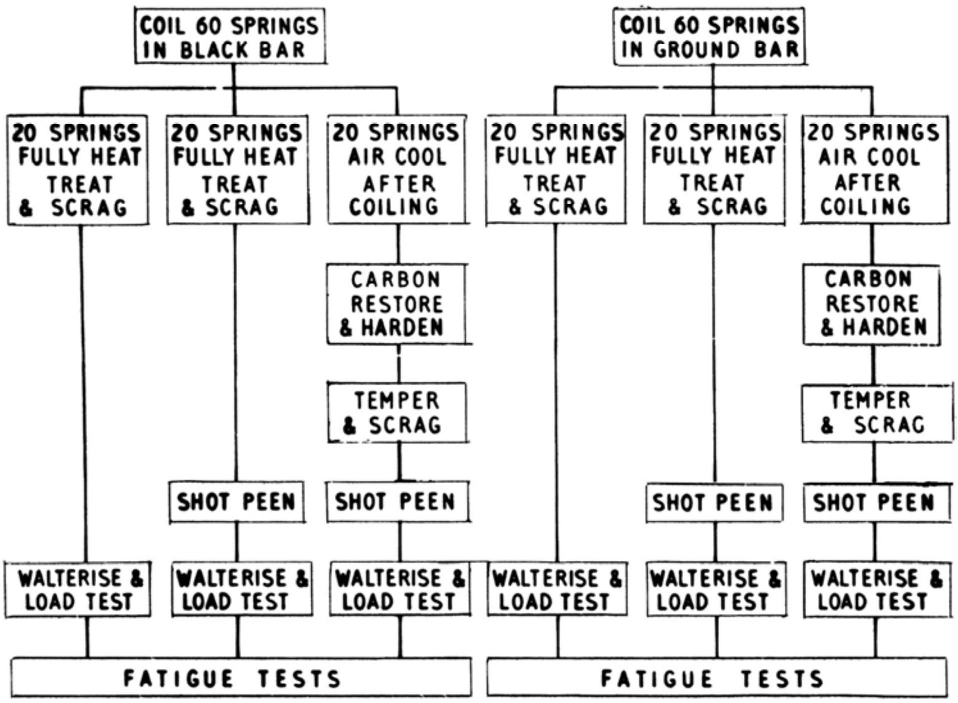
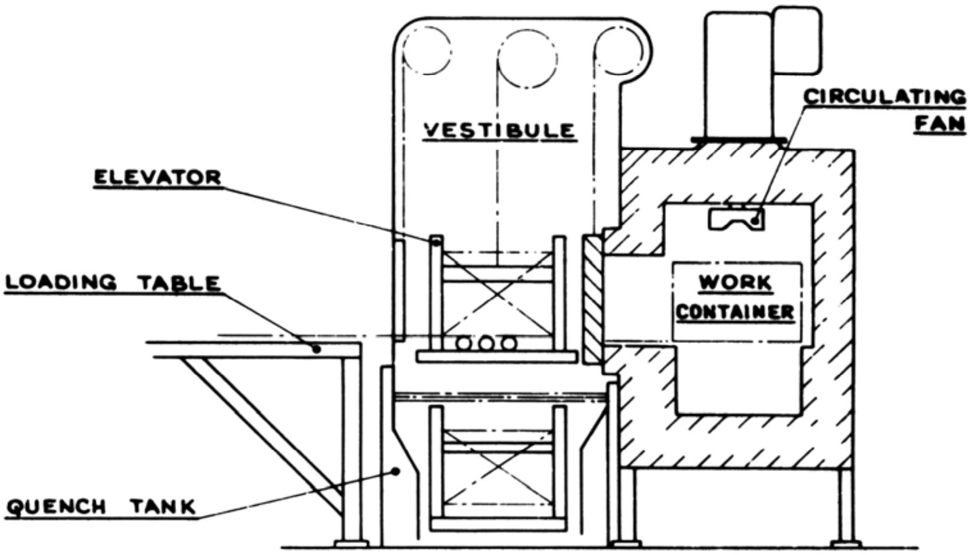


FIG. 2 FLOW SHEET FOR EACH SPRINGMAKER



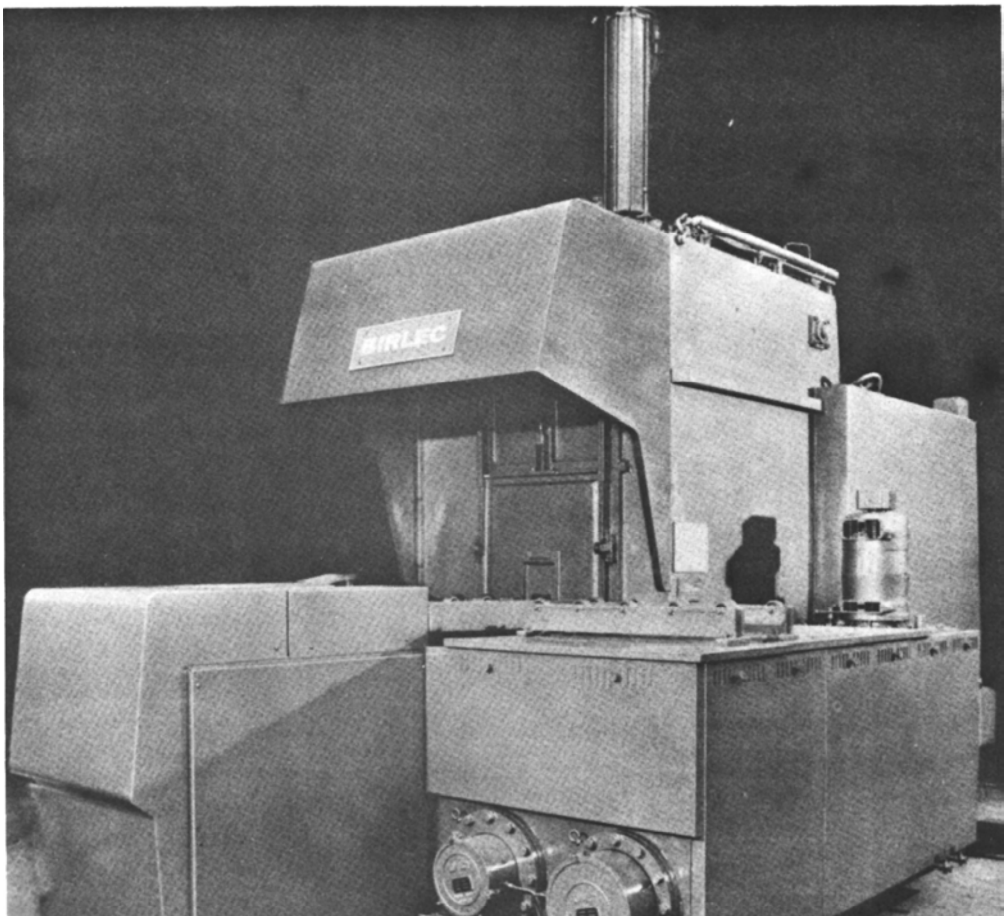


FIG. 3 SEALED QUENCH CARBON RESTORATION FURNACE

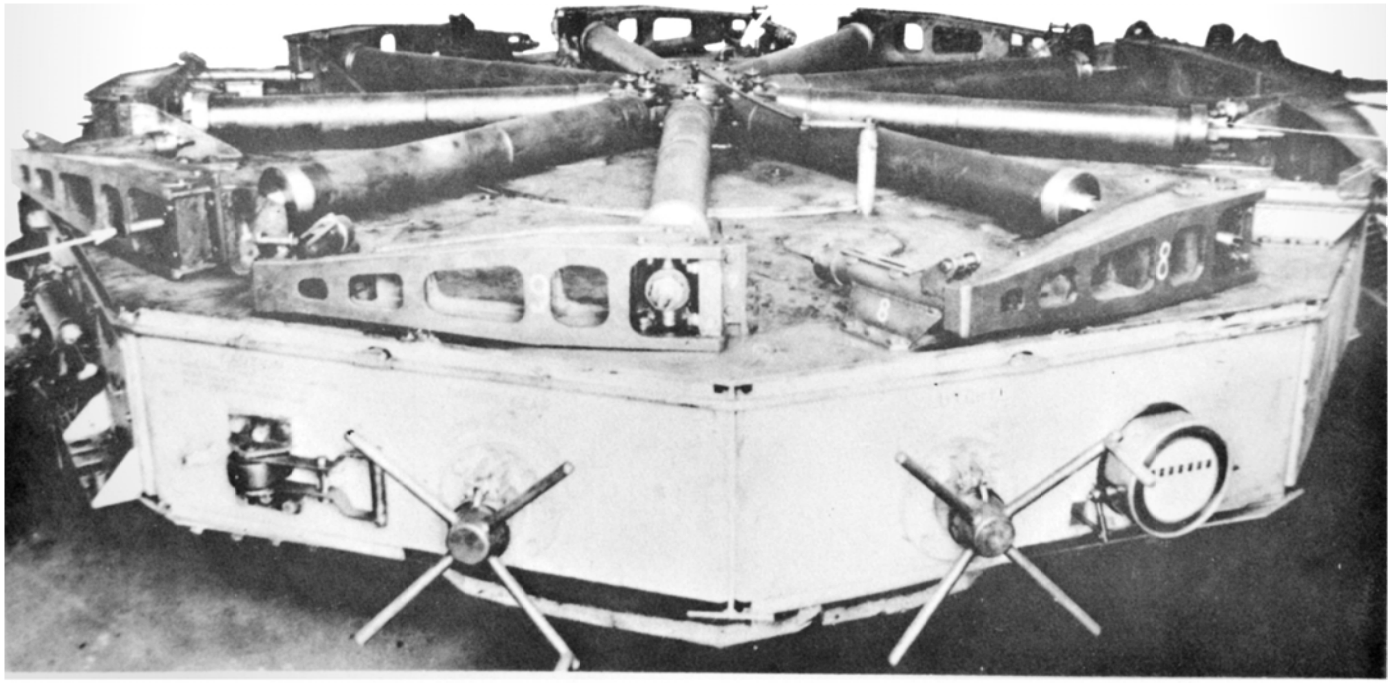


FIG. 4 FATIGUE TESTING MACHINE

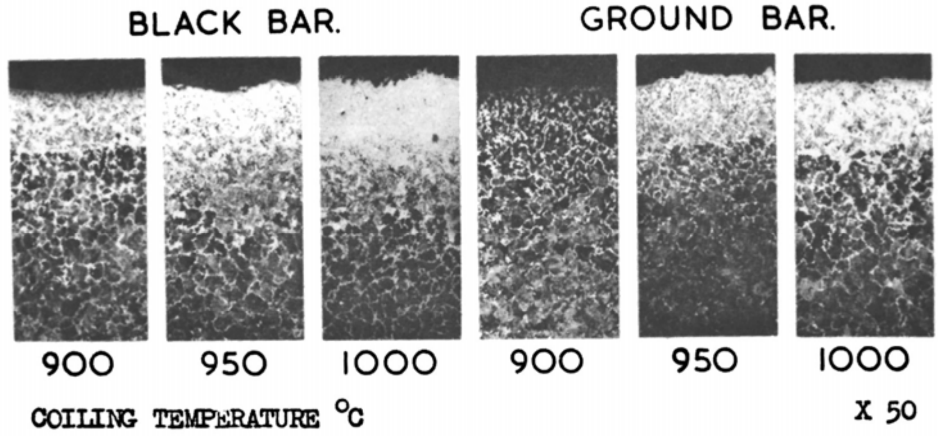


FIG. 5 DECARBURISATION OF SILICON-MANGANESE STEEL (STEEL A)

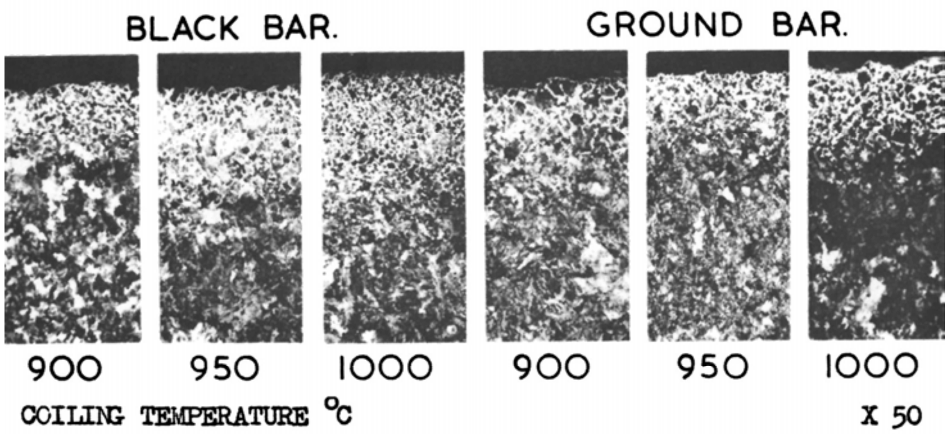


FIG. 6 DECARBURISATION OF HIGH CARBON STEEL (STEEL B)

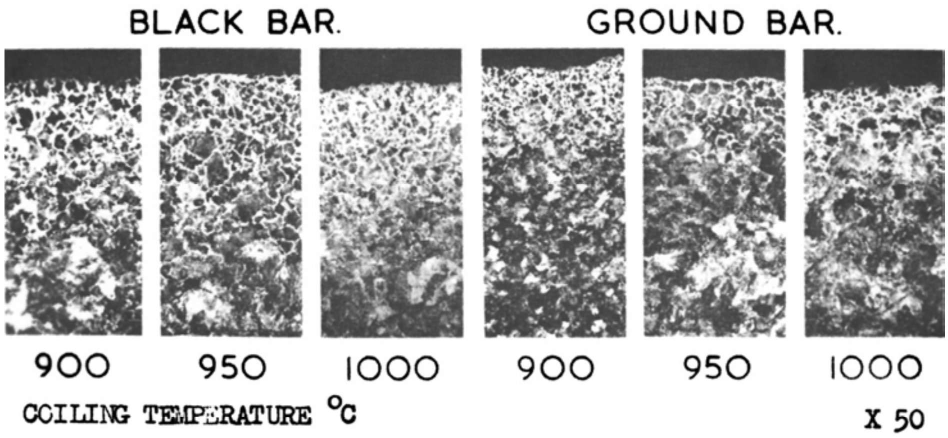


FIG. 7 DECARBURISATION OF MEDIUM CARBON STEEL (STEEL C)

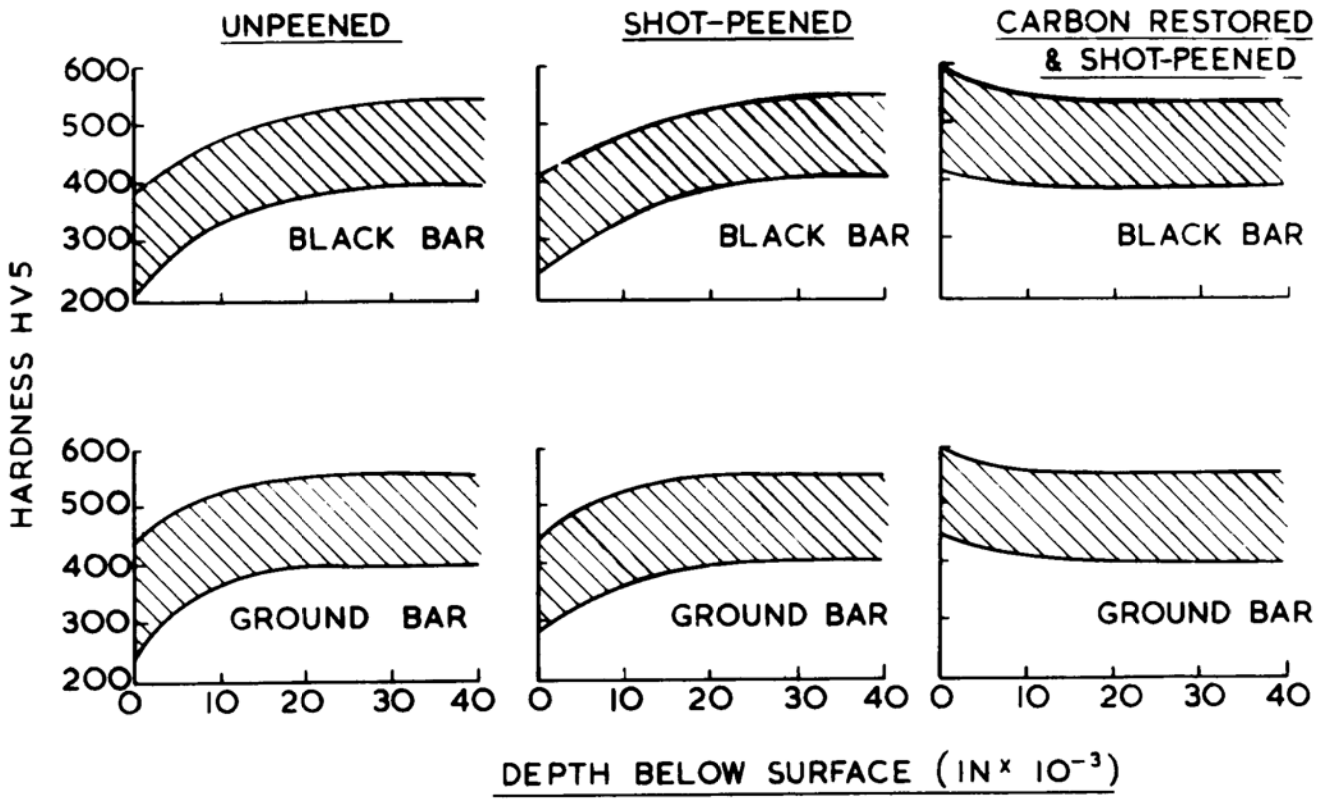


FIG. 8 HARDNESS/DEPTH RELATIONSHIP FOR DIFFERENT SURFACE CONDITIONS