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A new heat-treatment process overcomes temperature relaxation problems for spring users

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High-performance springs are demanding increasingly greater use of the potential available from the correct heat treatment of modern spring materials and application of current manufacturing technology. This is particularly true in the design of modern internal combustion engines where load loss of the valve springs when operating at running temperature will cause serious problems. Spring relaxation can be reduced to acceptable levels by a process known as 'hot prestressing' or 'hot scragging'. This paper discusses the mechanical and thermal processes involved in the production of high-performance springs and shows how it has been necessary to study the interaction of the variables in order to obtain an optimum compromise between fatigue life and stress–temperature relaxation. A new concept of resonant frequency fatigue testing was developed and a brief description of the design of the rig and control gear is included. The development of special-purpose machines to carry out hot prestressing on a large production scale is the logical conclusion to the work.

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AUTOMOBILE VALVE SPRING MATERIALS

There are two major categories of the high-performance wires from which the springs are coiled: (*a*) patented and cold-drawn carbon steel; (*b*) carbon and low-alloy steels which have been quenched and tempered subsequent to drawing to size. This latter type is usually termed 'prehardened and tempered wire'. Typical compositions are given in Table 1.

Both types of materials are produced to a tight specification for mechanical properties, freedom from decarburization and surface defects.

The low-alloy prehardened and tempered wires are becoming the preferred material since with suitable processing they offer the best combination of high fatigue performance with low relaxation.

SPRING DESIGN

The actual design of a valve spring is a very complex mathematical exercise requiring an analysis of the cam form and the mass of the moving components of the valve train. The final specification will define the dimensions and the loads. A typical spring is defined in Fig. 1.

MANUFACTURING STAGES

Automatic coiling machines are set up to coil the wire into the required form. The shape of the 'as-coiled' spring will allow for changes in geometry which will occur during later stages in manufacture due to the removal of certain stresses and the deliberate introduction of others.

The major stages are listed below (not always in this order):

(i) coil
(ii) first low-temperature stress relief
(iii) end grinding
(iv) shot peening
(v) second low-temperature stress relief
(vi) cold prestress
(vii) hot prestress.

Most of these operations will influence the fatigue and relaxation characteristics of the final product and these are discussed in the following sections of this paper.

EFFECT OF THE FIRST LOW-TEMPERATURE STRESS RELIEF

The purpose of the initial thermal treatment is to remove undesirable coiling stresses and to obtain an improvement in the elastic properties of the wire.

Some of the changes which take place as the temperature of treatment for cold-drawn wire is varied are illustrated by Fig. 2. It will be seen that although the maximum improvement in tensile strength and elastic

Table 1 Typical chemical compositions of valve spring wire

	C,%		Si,%		Mn,%		S,%		P,%		Cr,%		V,%	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Patented cold-drawn BS 5216, code HD	0·55	0·85	—	0·35	0·30	1·00	—	0·030	—	0·030	—	—	—	—
Prehardened and tempered chromium–vanadium, AVOT 2	0·47	0·53	0·15	0·30	0·70	0·90	—	0·020	—	0·025	0·80	1·10	0·15	0·25
Prehardened and tempered chromium–vanadium, AVOT 3	0·60	0·75	0·15	0·30	0·50	0·80	—	0·026	—	0·030	0·30	0·55	0·05	0·20

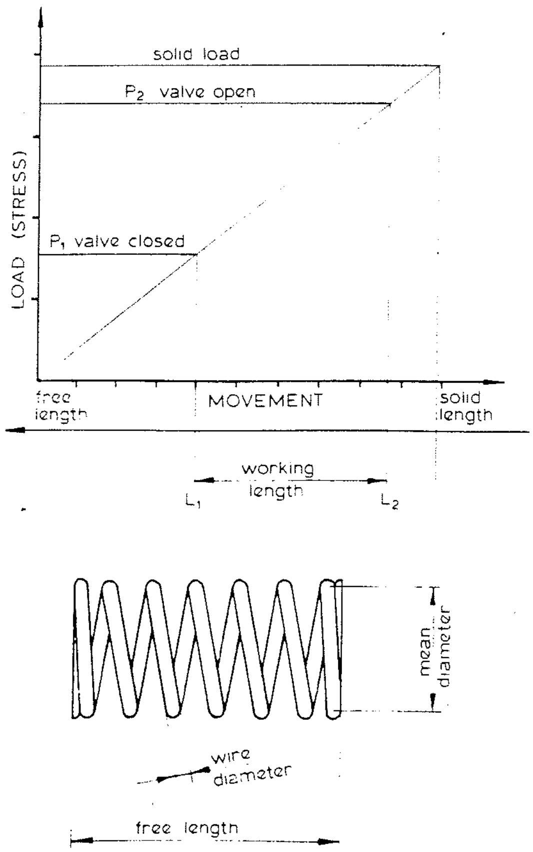
limit is in the order of 200°–250°C, the best fatigue and stress temperature relaxation occur at about 350°C. It is current practice to use the higher temperature and accept the fact that the optimum solid stress is not obtained.

The changes with treatment temperature for prehardened and tempered chrome–vanadium spring wire are shown by Fig. 3. In the case of this type of material, it is found that once coiling stress is relieved at temperatures above about 350°C increasing temperature will cause little change in fatigue performance; an improvement in stress temperature relaxation is however observed as the treatment temperature is increased up to a level approaching the original tempering temperature, which will be 400°–450°C depending on wire size and tensile strength.

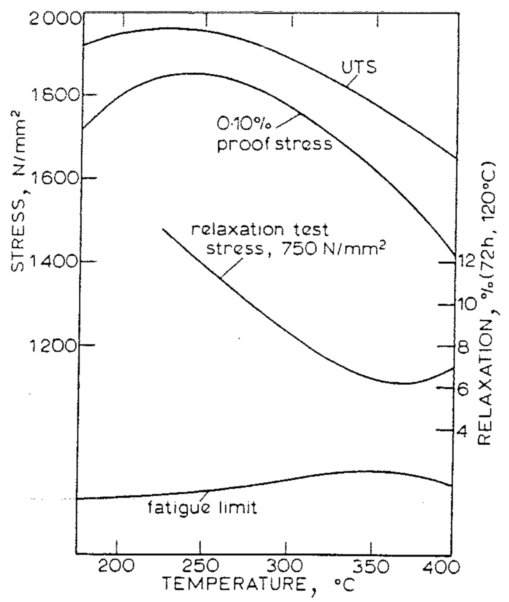
It is usual therefore to stress relieve after coiling at about 350°C for cold-drawn and at 400°–450°C for prehardened and tempered wires.

SHOT PEENING

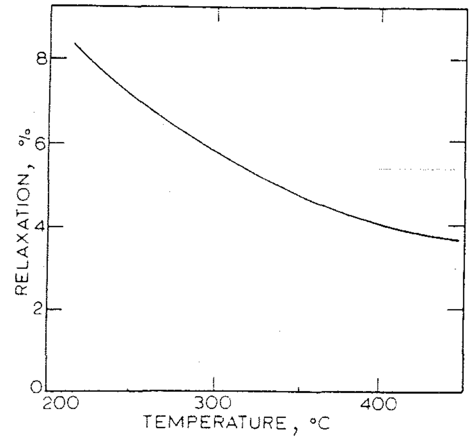
This process consists of bombarding the surface of the wire with spherical hard steel shot to produce a compressive stress in the surface layers of the wire. It is of particular importance to peen the inside diameter of the spring because this is where the greatest stress is developed when the coils are compressed. The size of shot, the speed of the impellor, and the time/bulk ratio are all important factors and are the subject of continuing research. Two types of shot are in current use: (*a*) hardened and tempered cast steel; (*b*) 'cut wire', which is hard-drawn high-tensile wire, cut to a length equal to its diameter and then processed to knock off all the sharp edges to produce a roughly spherical form. The latter is preferred by Salter Springs Ltd, the advantages being a consistent size and hardness, no breakdown, and long



1 **Definition of typical valve spring**



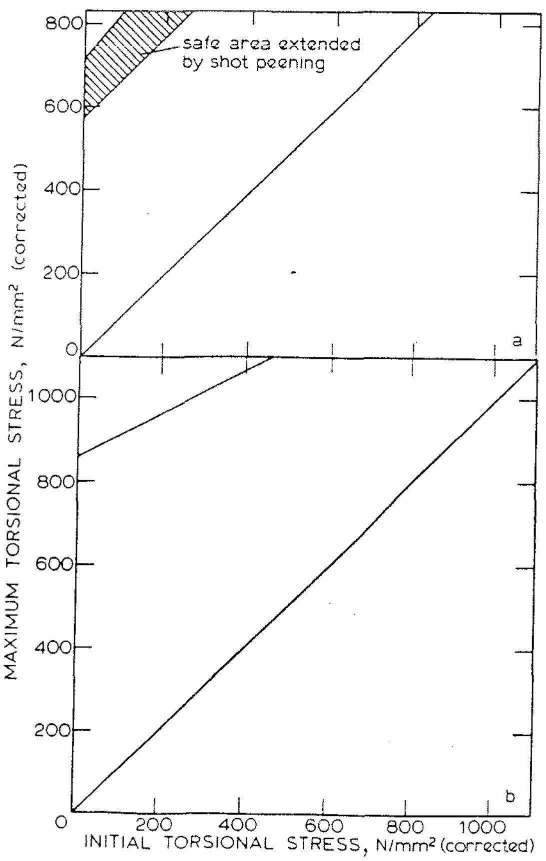
2 **Effect of low-temperature heat treatment on properties of cold-drawn valve spring wire**



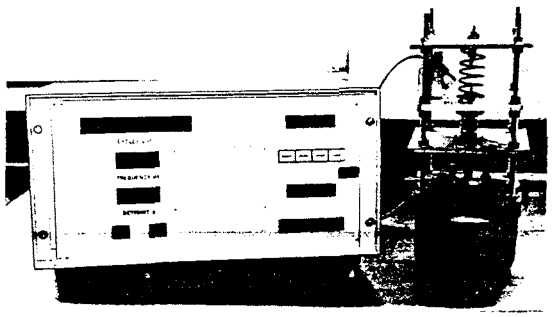
3 Effect of low-temperature heat treatment on relaxation of prehardened and tempered chrome-vanadium valve spring wire

service life. (A fractured shot particle can easily cause a notch in the wire surface with disastrous results.)

Shot peening elevates the fatigue limit and permits design with a much larger stress range than that obtained from un-peened springs. The results of fatigue research are normally presented in the form of modified Goodman diagrams, Figs. 4*a* and 4*b*.



4 Goodman diagram for *a* cold-drawn valve spring wire; *b* Avot 2 shot peened



5 Resonant frequency test rig and control unit

Controls of shot-peening process

The usual technique of measuring the effect of this process is to specify an 'Almen Arc Rise'. One or more hardened and tempered steel strip specimens are mounted on a hardened block and put through the process with the batch of work. Peening one side of the specimen only puts an unequal distribution of stress into the test specimen, which curves due to compressive stress on the convex face. The amount of curvature is a measure of the intensity and coverage of shot peening.

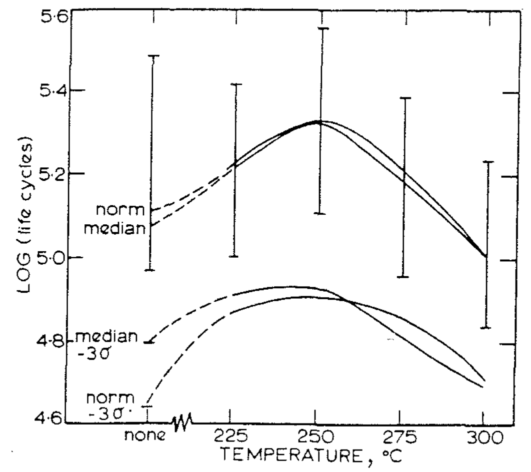
We have always been dissatisfied with a test specimen which bears no similarity to the components which it is supposed to represent. Attempts to relate Almen results to fatigue tests on actual springs have not been very convincing which is not too surprising considering the way in which a heavy block may randomly orientate when tumbled with a charge of several thousand springs. Moreover a spring is free to react dimensionally as the peening stress is introduced whereas the Almen specimen is restrained all the time.

A test method was therefore developed to produce quick fatigue results from test samples which are very similar to the springs being processed.

The testpieces are lengths of wire coiled into open-ended springs of regular pitch. Having been through all the process stages with a batch of springs, these testpieces are mounted into a rig and vibrating energy of low forcing signal power is applied to one end of the coils.

If the frequency of this vibration is adjusted to match the natural frequency of the test sample, a high amplitude can be generated in the free coils with a resultant stress range of sufficient intensity to cause early fatigue failure.

In practice, it is difficult to obtain a constant resonance condition due to such changes as ambient temperature and slight shift in the bearing points. This was overcome by having a manual control for initial set-up and then monitoring the amplitude of the spring coils using a magnetic transducer to feed a signal into an automatic control system.[1] (Developed by the Department of Electrical Engineering, University of Aston in Birmingham, Fig. 5.) The forcing signal frequency and amplitude are then adjusted continuously to maintain resonance. The system also terminates the test when the growth of a fatigue crack has altered resonance by a predetermined percentage. Thus all tests are terminated at a very similar stage of crack propagation and the scatter



6 Effect of post-shot-peening low-temperature heat treatment on fatigue life of Avot 3, obtained from resonant frequency technique

normally experienced with more conventional spring fatigue tests is reduced.

The technique provides a quick method of comparisons. For example, for shot-peening control against predetermined standards, three test springs are employed and a control chart is obtained from the average and range of the test results. The effect of varying process treatments can be established and the characteristics of different types of materials can be explored as a preliminary to conventional fatigue testing.

SECOND LOW-TEMPERATURE HEAT TREATMENT

The shot-peening process will produce what are commonly termed 'micro and macro' stresses depending upon the angle of incidence at which the shot particle contacts the surface of the wire. The pure compressive macro stress is beneficial but the micro stress may reduce the elastic limit. A further low-temperature heat treatment will remove the undesirable component of the induced stresses but if carried out at an excessive temperature will remove the beneficial stress and so reduce the fatigue life of the springs.

It has also been found that relaxation is increased by shot peening but reduced again as the temperature of the second stress-relieving treatment is increased.

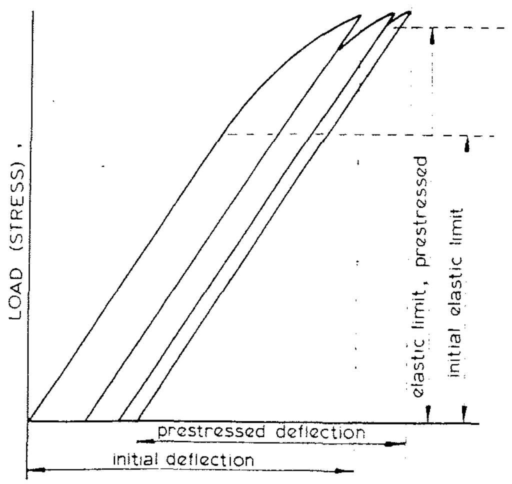
The effect of the temperature of this treatment on shot-peened springs had been studied using the resonant frequency technique (*see* Fig. 6). This indicates that the optimum temperature for chrome–vanadium prehardened and tempered wire is in the order of 250 °C.

COLD PRESTRESSING

This process increases the apparent elastic limit of the spring material by introducing a stress pattern in which the elastic limit of the outer fibres is exceeded so that plastic deformation occurs, while the stress further towards the neutral axis being progressively lower is below the elastic limit. This is done by manufacturing the spring with a free length such that the theoretical elastic limit of the spring material is exceeded when the maximum possible compression is applied (solid height). When this load is relaxed, the fibres of the core attempt to recover their original position but are restrained by the plastically deformed outer fibres; these outer fibres, being strained by the recovery stress of those inside, only partly recover their original position and so a condition of equilibrium exists in which the resultant stress pattern allows a solid height which is greater than that which is theoretically possible. Therefore the load capacity of the spring is improved and the optimum use of the material is obtained. In practice the process of prestressing (or 'scragging' as it is known in the trade) has to be carried out three times or more to obtain a stable condition (Fig. 7). After prestressing, springs may show slight change in load over a period of time, or if 'bounced', and this probably accounts for some of the variations in load between different inspections.

The extent to which a spring is prestressed will be determined by the solid stress needed to meet the load requirements and the mechanical properties of the spring wire, which vary according to the wire diameter for both cold-drawn and prehardened and tempered materials. In some cases the physical proportions of the particular spring design inhibit the amount of prestress because the spring will distort if closed solid.

This cold prestressing operation has little influence on the relaxation of springs which need to be finally hot prestressed but will often be carried out possibly with only one closing, or 'scrag', in order to make the spring more stable and to reduce the total time taken for hot setting, particularly when the spring is heated by a resistance technique discussed later in this paper.



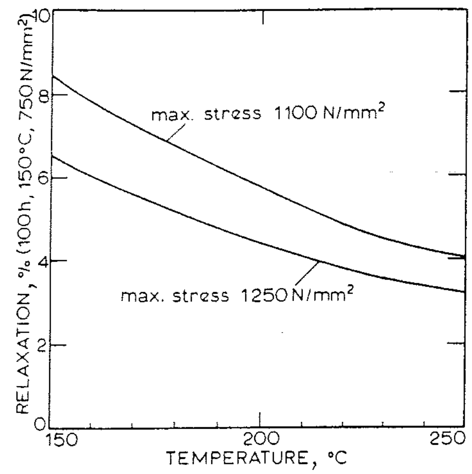
7 Simplified mechanism of prestressing

HOT PRESETTING

This is the operation which needs to be added to normal spring manufacture if it becomes known that the relaxation of an otherwise desirable spring design is more than that which is acceptable. There are several combinations of the methods which may be employed to hot prestress a compression spring. The practicability and technical aspects of these may be considered as follows below.

Method (a)

This consists of clamping the spring either solid or to a predetermined length and then heating spring and jig for



8 Effect of hot prestressing temperature and stress on relaxation of shot peened Avot 2

sufficient time to allow the major part of the 'creep' to take place. At the conclusion of this, the spring can be cooled to ambient temperature while in the jig, or quenched. Alternatively, the spring can be ejected from the jig and cooled in air or quenched.

In this technique, the best results are obtained if the spring is quenched while under restraint so that the maximum amount of prestressing is obtained. If the springs are removed from the jig when hot, a proportion of the induced residual stress will be dissipated by the simple stress-relieving effect of the heat contained in the spring.

The economics of this method are not attractive because of the need to employ large numbers of heavy jigs which are continually being heated and cooled. The jig is likely to weigh more than the spring. There may also be problems in making the jigs adaptable for differing designs.

Method (b)

This consists of heating the spring for a particular time and temperature, then closing to solid or predetermined length, followed by quenching while under restraint. This technique is likely to be more economic if the springs are continuously fed through an efficiently designed heating system. The transfer and closing mechanisms do not pose any serious design problems.

The springs, however, are cooling as soon as the transfer and clamping have been completed and the resultant effect on relaxation will not be as effective as methods in which the springs are under restraint while the heat is being introduced.

This method is being used on a commercial scale and in many cases is producing acceptable relaxation values.

Method (c)

The most attractive method, from the economic and technical points of view, is one in which just enough energy is used to bring the spring up to temperature while it is compressed to a level of stress such that the desired amount of creep is allowed to occur and the process is cut off at a particular point for individual springs so that the resultant loads at length are very consistent.

Accordingly, experiments were carried out to examine the feasibility of using low-voltage a.c. to heat the spring by resistance and then to devise a system which would stop the process at the necessary point.

The results indicated that satisfactory relaxation could be obtained together with a close load tolerance (of the order of 3–4%), often better than normal 'cold scragged' spring production. It was also found that provided the electrical contact plates at each end of the spring are correctly designed and maintained and a critical force is applied before the current is passed, consistent heating and freedom from 'arcing' can be established. 'Spark guards' can be integrated into the circuits as an added safety factor. The applied current can be adjusted for a particular design of spring to ensure that the temperature of the spring does not exceed that at which the fatigue performance would be adversely affected. (The springs are shot peened when this operation is carried out.)

Finally, a system of mechanical handling and automatic sequencing was developed for which patents are now pending.

The equipment which was developed has progressed through several stages of refinement and is now completely reliable on a high-volume basis. The economics are satisfactory and sample checks are regularly carried out to prove the fatigue and relaxation properties of springs under dynamic stress. Further confidence in the technique has been obtained by extensive road testing and by the performance of standard production vehicles which are now being regularly fitted with valve springs which have been hot prestressed by these machines.

Effect of hot prestressing

The extent to which relaxation of a spring under elevated temperature can be reduced is mainly controlled by two factors. The first is the stress level at which the hot prestressing is terminated. If this stress is increased there will be a reduction in relaxation. The second factor is the temperature of hot prestressing. If unpeened springs are considered first, there is a reduction in relaxation as the temperature of hot prestressing is increased to about 400°C for prehardened and tempered spring wire and about 350°C for cold-drawn spring wire. If the springs have been shot peened the temperature of hot prestressing is limited by the effect this treatment will have on the fatigue limit, as previously discussed. However a reasonable compromise can be obtained if the temperature is not allowed to exceed 250°C, Fig. 8. The relaxation shown by these curves was obtained by static tests. If these conditions are repeated under dynamic conditions simulating actual valve gear operations it will be found that the relaxation will be considerably reduced. In some instances it will be only half of the static relaxation.

CONCLUSIONS

This paper has attempted to show that a relatively simple heat treatment such as stress relieving, combined with the mechanical processes of spring making and other processes such as shot peening, can be studied to optimize them for performance under high fatigue stress and elevated temperature conditions.

The use of the hot presetting technique is by no means confined to automotive valve springs. There are many other applications for the use of heat-stabilized springs made from low-cost materials. The technique is applicable to some of the more highly alloyed spring materials and it is anticipated that the application of hot presetting to some of the problem areas in which exotic alloys are at present used may allow the use of lower alloys with considerable cost saving and possibly better all-round performance.

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REFERENCE

1 H. A. BARKER *et al.*: *Proc. Inst. Electr. Eng.*, 1978, **125**, (9)