

GUIDE TO THE SELECTION OF SURFACE TREATMENTS FOR THE IMPROVEMENT OF FATIGUE STRENGTH OF STEELS

1. INTRODUCTION

Fatigue cracks usually begin at the surface of a component in a region of high stress. Because of this it is often possible to improve the fatigue strength of a component by the application of a suitable surface treatment. Improving the fatigue strength of a material can have many advantages. The mass of a component may be reduced whilst still allowing the component to perform its original task. Components may be operated at higher stress levels for the same life, or at original stress levels with an increased life. This Item provides a guide to the selection of the surface treatment that most closely matches requirements. It does not cover processes such as autofrettage or scragging that result in working that affects more than the surface of a component.

Three major groups of surface treatment that improve the fatigue strength of a steel are covered. These are (i) mechanical, which improves the surface finish or works the surface to induce compressive residual stress and/or raise the yield stress, (ii) thermal, which transforms the surface layers to induce compressive surface stresses and (iii) thermo-chemical, which alters the structure of the surface of a steel to enhance its properties and/or induce compressive surface stresses. This Item gives details of the main processes in these groups, and their effects on the fatigue strengths of steels and some cast irons. Table 3.1 is a diagrammatic representation of the processes covered by this Item.

2. NOTATION

Both SI and British units are quoted but any coherent system of units may be used.

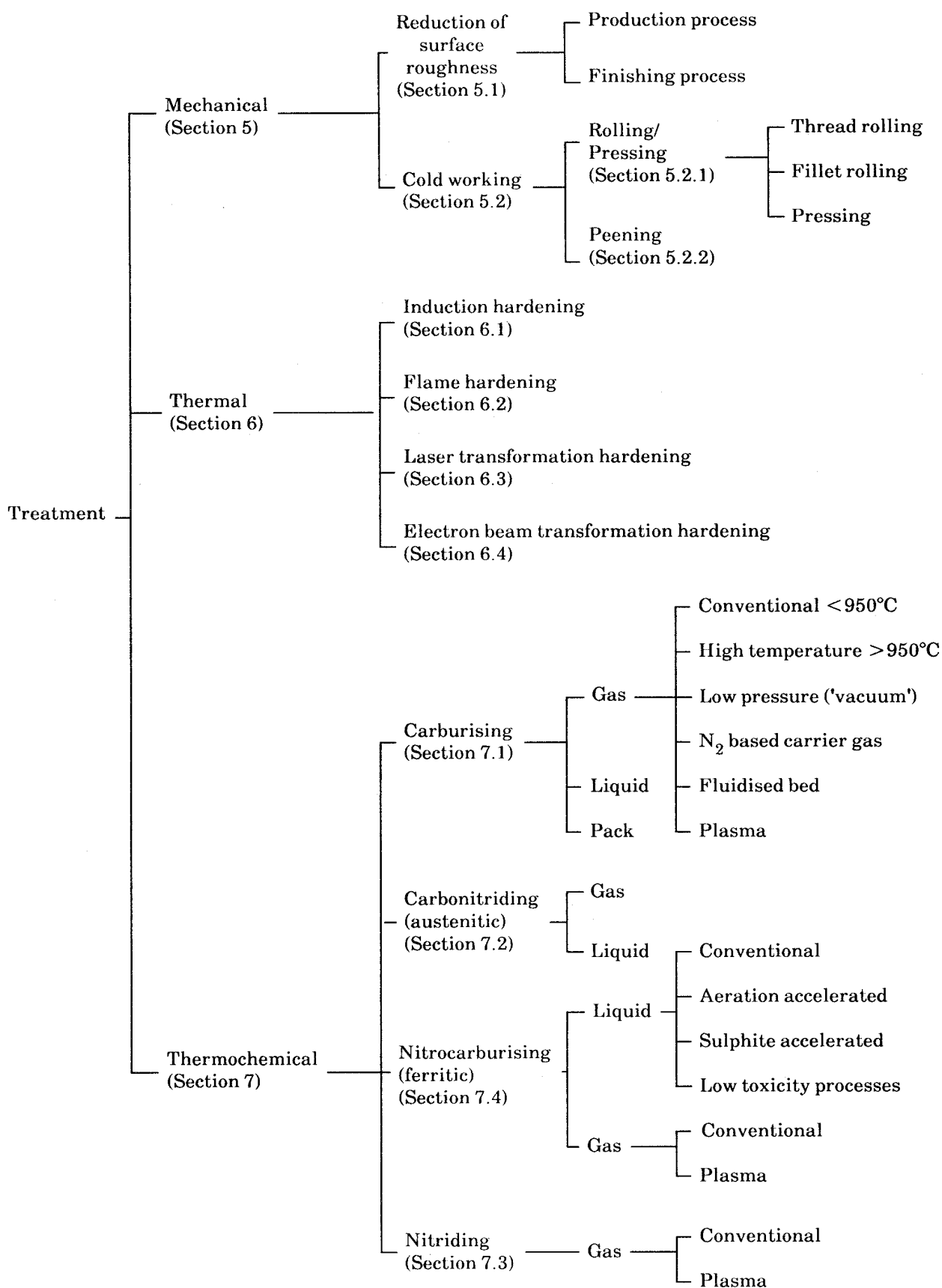
f_n	nominal stress due to loading	N/m ²	lbf/in ²
f_p	proof stress of material	N/m ²	lbf/in ²
f_t	tensile strength of material	N/m ²	lbf/in ²
HV	Vickers hardness value		
K_t	elastic stress concentration factor		
N	number of load cycles	c	c
$S_{a0(\infty)}$	fatigue limit of material at zero mean stress	N/m ²	lbf/in ²
δ	case depth	m	in

3. IMPROVEMENT BY GENERATION OF RESIDUAL COMPRESSIVE STRESSES

Many surface treatments improve the fatigue life of components by introducing beneficial compressive residual stresses into the surface region, particularly at notches. Because of the importance of this method of fatigue strength improvement, and its appearance in many of the treatments discussed in this Item, the mechanism by which improvement occurs is described in this section. The following sections explain how residual stresses can be generated and how they affect the working stress of a component and influence its endurance.

It should be noted that post-process treatments such as grinding or tempering should not be carried out as they can remove beneficial compressive stresses induced in the surface of a component. Also, any local machining after treatment may cut through the compressive layer at the surface so negating any beneficial effect of that layer.

TABLE 3.1 Surface Treatment Processes



3.1 Generation of Residual Compressive Stresses

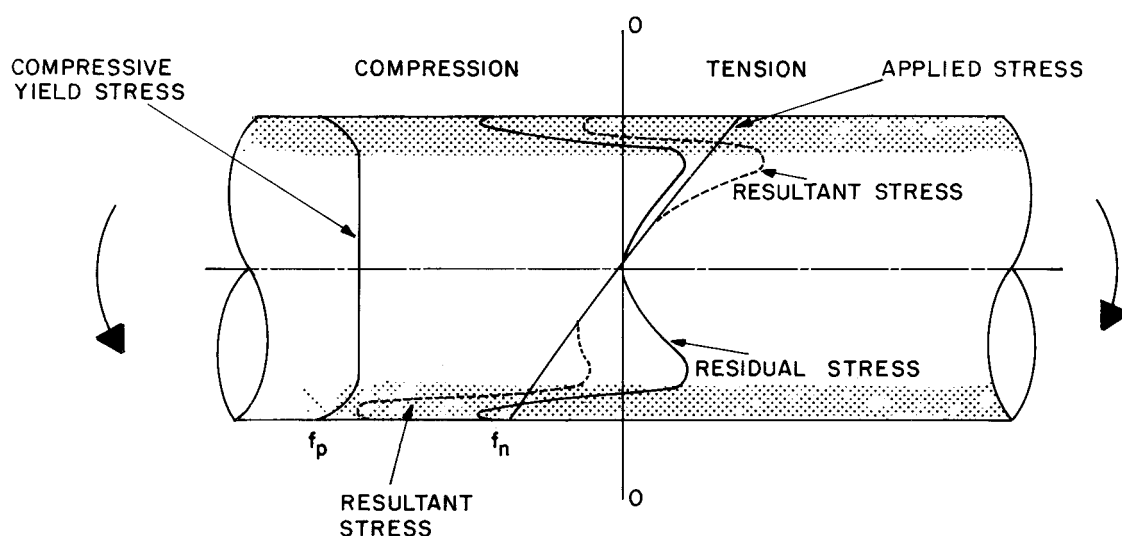
Beneficial residual compressive stresses at a surface can be generated by mechanical, thermal or thermo-chemical means. In all cases residual compressive stresses at the surface are balanced by residual tensile stresses below the surface. The generation of residual compressive stresses by purely mechanical means is carried out by deformation processes such as rolling and peening which are sufficient to cause plastic flow.

Thermally induced residual surface compressive stresses result from the volumetric change that occurs on the transformation of austenite to martensite in a steel surface on quenching from the austenising temperature of 850° (1562°F) and above. Residual stresses can also result from quenching a steel subjected to a temperature gradient, a self-equilibrating field of residual stress being retained in place of the temperature gradient.

The mechanism that operates in thermo-chemically treated steels is due to the volumetric changes that accompany the diffusion of carbon in a carburised case or nascent nitrogen in a nitrided case. In the carburising process the surface layers transform from austenite to martensite, and in nitriding, stable nitrides are formed which occupy a greater volume than the alloying element in solution. Thus, the resulting volumetric incompatibility of the metallurgical phases leads to the creation of residual compressive stresses at the surface.

3.2 The Effect of Residual Stresses

The effect of a residual stress on the fatigue limit of a material is similar to that of a super-imposed static mean stress, compressive residual stresses being beneficial to fatigue strength, tensile residual stresses detrimental. Sketch 3.1 illustrates the stress distribution in an unnotched component having a compressive residual stress at the surface and which is subject to a bending moment. As the sketch illustrates the maximum tensile stress on the surface is considerably reduced. It can also be seen from the sketch that the compressive residual surface stress combined with the compressive stress produced by the bending moment can approach, or exceed, f_p , the proof stress of the material.



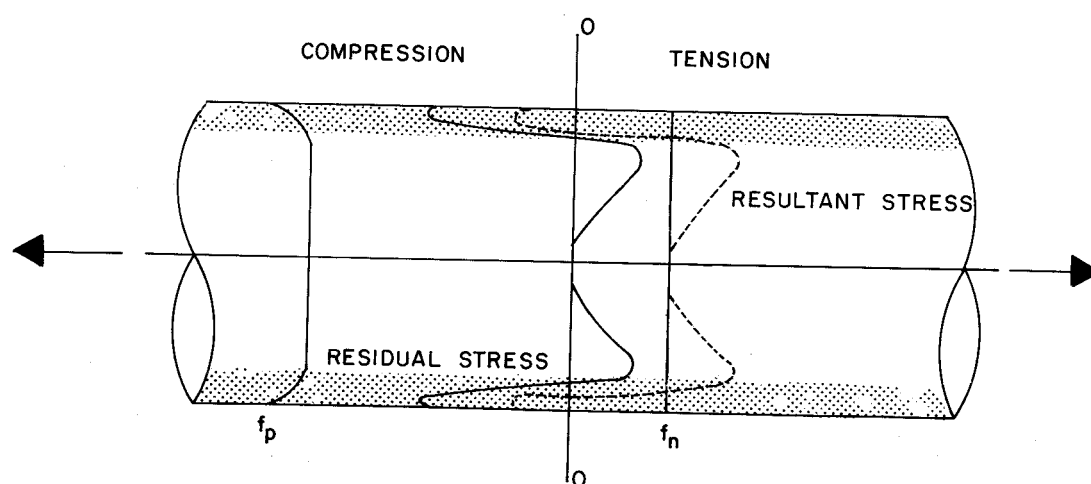
Sketch 3.1 Stress distribution of unnotched component in rotating bending with compressive surface residual stress

Compressive residual stresses do not have a pronounced effect on the minimum fluctuating shear stress required to initiate and develop a micro-crack but can profoundly affect the subsequent propagation of small cracks under direct stress. Residual compressive stresses of sufficient magnitude and depth will prevent a small crack opening and so either retard its growth or cause it to remain dormant unless the tensile stress level is raised. Therefore, compressive residual stresses will, for a given stress range, increase the fatigue life of a component.

If the residual compressive stresses affect only a very thin surface layer, very little benefit in fatigue life over that of the untreated material will be obtained. Also, in order for the residual stress to be effective the depth to which it is induced must be greater than that of surface roughness features.

The effect of residual compressive stress on the fatigue life of a component is also dependent upon the type of loading applied. The higher the alternating stress range applied the lower the improvement in fatigue life as it becomes easier for a micro-crack to develop into a small crack. In most cases, and especially for plain components, the effect of residual compressive stress at the surface is less pronounced in reversed direct loading than in bending loading. This is because direct stressing subjects the cross-section of the component to a uniform stress, which in the tension half of the cycle is reinforced by the complementary tensile stresses that exist at the case-to-core interface, as illustrated by Sketch 3.2. With very deep cases it is possible that the resultant high tensile residual stresses in the core will initiate and promote rapid crack propagation causing the fatigue limit to be lowered. With very thin cases it is possible that the magnitude of the applied load at the case-to-core interface, combined with the residual tensile stresses present, will be enough to cause failure.

A residual stress may be altered by any subsequent plastic deformation induced by cyclic stressing. Induced compressive residual stresses have the greatest beneficial effect on the fatigue strength of notched components, where the applied nominal stresses are less than the unnotched fatigue limit of the material, the benefit increasing with both notch sharpness and yield stress to fatigue limit ratio. If, thereafter, the cyclic stressing is sufficient to relax the residual stresses early in the life of the component there is no longer a beneficial effect on its subsequent fatigue strength.



Sketch 3.2 Stress distribution in unnotched component under axial loading with compressive residual stress

4. PROCESS SELECTION

Tables are provided for use in the selection of a suitable surface treatment. It must be remembered that the final choice of treatment is heavily influenced by the cost, convenience and availability of a process. Also, in some circumstances, several treatments will be capable of providing the required improvement in fatigue strength. In such cases other aspects of the treatments may indicate that which is most suitable.

Two methods of selection are presented. The first is based on current good practice. Table 9.2 sets out a list of common components together with the surface treatments usually applied to them and this may be used as a guide to an acceptable treatment.

The second method is iterative and involves selection of the process from basic considerations. Table 9.3 gives a chart of a possible route through process selection and provides a systematic approach to considering the various factors. Tables A1.1 to A1.11, in Appendix A, give a uniform tabular presentation of the features of each of the treatments covered by this Item and this can be used with the steps listed in Table 9.3. Alternatively, Table 9.4, which summarises the information in Tables A1.1 to A1.11, may be used.

5. MECHANICAL METHODS

5.1 Improvement by Reduction of Surface Roughness

The initiation of micro-cracks is associated, in general, with a free surface, and therefore the fatigue strength of a material, particularly at long endurances, depends on the roughness and condition of the surfaces created by the particular manufacturing techniques used. Usually, the better the surface finish the greater the improvement in fatigue life. Data Item No. 74027* gives details of the full effect of surface finish on fatigue strength and relates this to the machining processes available.

5.2 Cold-Working

This section gives details of the mechanical processes that can be used to enhance the fatigue life of a steel component. In all cases the major mechanism is the creation of surface residual compressive stresses.

The term cold-working signifies the operation of plastically deforming a metal at a relatively low fraction (less than one half) of its absolute melting temperature. The resulting plastic strain affects fatigue properties in two main ways. Firstly, mechanical strength values (that is the yield strength and, to a lesser extent, the tensile strength) are enhanced, and residual stresses are produced by the inhomogeneous plastic strain. Secondly, a residual compressive stress is introduced into the worked surface. The effect of this on fatigue strength is covered in Section 3 of this Item.

An illustration of the improvement in fatigue strength that can be gained by an increase in static mechanical strength due to cold-working is shown by Tables 5.1 and 5.2. Table 5.1 shows the effect of cold-working on a typical mild steel, and Table 5.2 on an 18/8 stainless steel.

The two major cold-working processes are rolling or pressing and shot-peening. These are covered in detail in the following sections. It should be noted that, especially if the sections treated are thin, the fatigue strength improves with increasing intensity of peening or rolling to a maximum value, after which the fatigue strength begins to decrease rapidly due to excessive internal tensile stresses. In thin sections this effect can occur at a relatively low level of cold-working owing to the limited area available to provide the balancing tensile stress.

* Data Item No. 74027 "The effect of surface roughness on the fatigue limit of steels (at zero mean stress)".

TABLE 5.1 Significance of cold-working on the static and fatigue strengths of a steel*

Condition of rolling	Hardness HV		Tensile strength MN/m ² (lbf/in ²)		Fatigue strength MN/m ² (lbf/in ²)
	min.	max.	min.	max.	
Annealed	—	105	280 (41 000)	350 (51 000)	158 (23 000)
† Skin passed	—	115	280 (41 000)	370 (54 000)	163 (24 000)
Quarter hard	110	135	350 (51 000)	420 (61 000)	173 (25 000)
Half hard	135	165	420 (61 000)	540 (78 000)	216 (31 000)
Hard	165	—	540 (78 000)	—	270 (39 000)

* Nominal composition: C 0.12%, Mn 0.8% max., S 0.05% max., P 0.05% max., Fe remainder.

† Skin passed refers to the operation of a light cold-roll pass to size after the hot-roll, pickle and de-scaling stages.

TABLE 5.2 Extent of work-hardening capacity of 18/8 stainless steel

Condition of rolling	Tensile strength MN/m ² (lbf/in ²)	Rotating bending fatigue strength MN/m ² (lbf/in ²)
Annealed (1100°C)	650 (94 000)	230 (33 000)
Partial cold-work	770 (112 000)	430 (62 000)
Further cold-work	930 (135 000)	510 (74 000)

5.2.1 Rolling, Pressing

The cold-working processes of rolling or pressing are particularly effective when used, for example, on a wrought alloy having a geometric stress concentration or other localised region which adversely affects the fatigue strength of a component. Owing to the localised nature of these processes, and the fact they are best suited to axisymmetric components, specific uses have arisen. Rolling, the most common of the processes, has found particular use in the improvement of fatigue strength of threads and fillets, whereas pressing is typically used for the alleviation of fatigue at holes in shafts.

These processes can be used on large surfaces and entire complex components, but the high forces involved lead to a significant risk of distortion, or induced tensile stress at an untreated free surface. This Item covers the applications deemed most useful for this type of surface treatment.

5.2.1.1 Thread rolling

The method of manufacture has a major influence on the endurance of steel screw threads. Although many different threaded fasteners are available, the fatigue problem is common to all. The thread, being a loaded projection, has a high stress concentration factor at its root. Rolling of the thread plastically deforms the material introducing beneficial compressive stresses, as explained in Section 5. An additional benefit of rolling is an improvement in surface finish which also increases the fatigue strength at long endurances.

It is important that any heat treatment required be carried out before thread rolling for the following reasons.

1. The beneficial compressive stress induced by cold-rolling is relaxed by creep when low alloy steels are heated above 350 to 400°C (660 to 750°F).
2. The effects of even microscopic decarburisation at the root radii of the threads can be detrimental to the endurance of a screw thread.

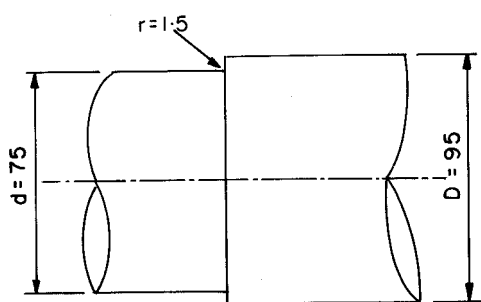
Quantitative data are available in Data Items Nos 80028* and 84037†.

5.2.1.2 Fillet rolling

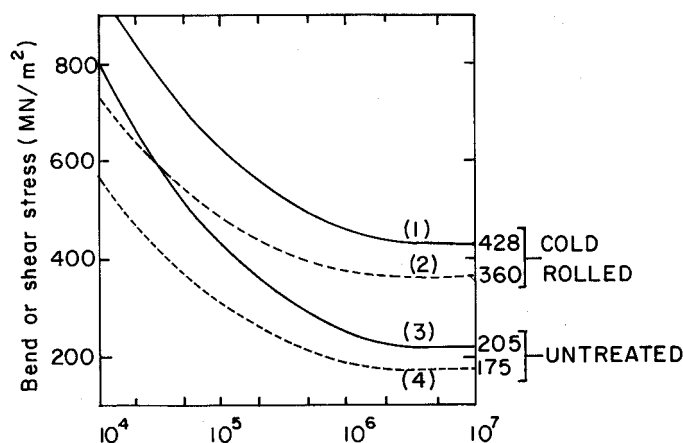
In order to be functional, components cannot be made without some geometrical discontinuities, such as, for example, changes of section in shafts. Most discontinuities have fillet radii to alleviate the problem of stress concentration and, in many cases, these can be beneficially treated by cold-rolling.

In common with most cold-working processes the effectiveness of surface rolling depends on the degree of plastic deformation and the magnitude and depth of the residual compressive stresses produced. For fillet rolling it is normal practice to use a hardened steel roller with a relatively small contour radius that is loaded onto the fillet of the workpiece, the roller being fed along as the workpiece rotates. In general an increase in rolling load leads to an increase in fatigue strength, but increased fillet distortion accompanying higher loads can cause problems. The high pressures necessary with hard steels can lead to significant surface damage.

A typical example of the improvement in endurance resulting from fillet rolling is shown by Sketches 5.1a and 5.1b. Sketch 5.1a shows a typical shouldered shaft in steel 826 M31 (BS 2S 96), of tensile strength 925 MN/m² (134 000 lbf/in²), containing a geometric stress concentration factor of $K_t = 2.5$ at the fillet radius. Curves (1) and (2) of Sketch 5.1b demonstrate that cold-rolling applied to the fillet radii restores its fatigue strength to the values for unnotched steel of ± 428 MN/m² (± 62 000 lbf/in²) in bending and ± 360 MN/m² (± 52 200 lbf/in²) in shear. Typically, increases of between 1.25 and 2.0 times the fatigue strength can be expected from the cold-rolling of fillet radii.



Sketch 5.1a Shouldered shaft (all dimensions in mm) in steel 826 M31 (BS 2S 96).



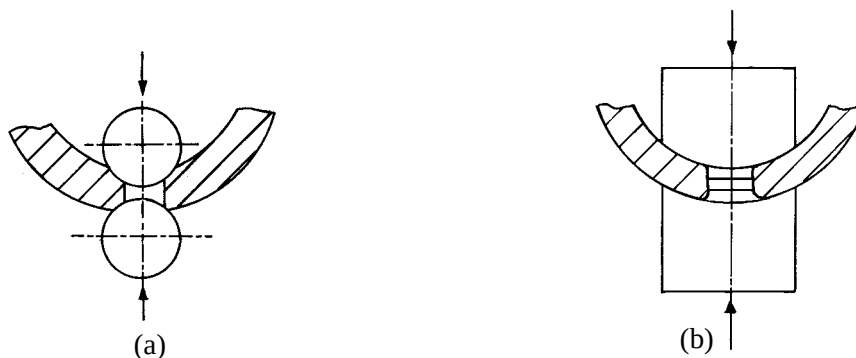
Sketch 5.1b Improvement of fatigue life in bending and torsion by cold-rolling the fillet radii of shafts in steel BS 2S 96: stress–endurance curves – (1) and (3) tested in rotating bending, (2) and (4) tested in reversed torsion.

* Data Item No. 80028 “Fatigue strength of large steel bolts and threaded connections under axial loading”.

† Data Item No. 84037 “Fatigue strength of external and internal steel screw threads under axial loading. (Standard forms not greater than 1.0 inch diameter.)”.

5.2.1.3 Pressing

Wherever holes break a surface in a region of high fluctuating stress there is the possibility of fatigue cracking. A well-known example is oilways in the webs and journals of crankshafts. The simple operation of cold-forming a small radius around the lip of the oilway introduces a residual compressive stress which can restore the fatigue strength of the shaft to virtually that of the undrilled condition.



Sketch 5.2 Cold forming of hole bore by (a) a ball of hardened steel and (b) a special form tool

The results of fatigue tests on optimally cold worked holes in the webs of crankshafts and ring specimens show a fatigue strength almost equal to that of the undrilled shaft. Typically, pressing can increase the fatigue strength of a component by a factor of between 1.25 and 2.

5.2.2 Peening

Peening is a cold-working process which consists of bombarding the surface of a component with small steel shot, glass beads or other rounded particles under carefully controlled conditions. Each shot particle causes the material to yield at the surface and so produces a residual compressive stress. These residual stresses can approach a value equivalent to 80 per cent of the tensile strength of the material, dependent upon the intensity of peening. The depth of the compressive layer is also affected by the peening intensity but is generally between 0.5 and 1 mm (0.02 and 0.04 in), although greater depths can be achieved on certain materials. These induced surface residual compressive stresses counter surface tensile stresses arising from manufacturing operations, stress raisers and loading conditions, thus extending a component's fatigue life. Section 3 gives details of this effect.

Whilst shot peening can be used on low carbon steels to improve the fatigue strength, proportionally more benefit is accrued on higher strength steels having f_t above 1200 MN/m^2 ($175\,000 \text{ lbf/in}^2$).

A common source of surface defects are tool marks remaining from the forming operation. In most cases shot peening can negate the notch effect of these defects in one of three ways. If the material is fairly soft (below 400 HV) and the defect shallow, the peening effect will tend to blend the defect due to the plastic flow of the surface. On harder materials shot size and/or intensity can be varied, either using a fine shot which is small enough to peen the root of the "notch", or a larger shot and higher intensity to produce a layer of compressive stress that extends beyond the depth of the discontinuity.

Shot peening is of less value in low cycle/high stress/high temperature combinations. Shot peening is at its best in high cycle fatigue cases, reducing scatter of fatigue endurance and increasing the fatigue limit. Components subject to cyclic loading that receive occasional peak stresses above yield are not generally suitable applications because such peak stresses can relax the induced compressive stress.

Peening, while in the main being an excellent process for enhancing fatigue life, does have some drawbacks.

Improvements in fatigue strength are achieved only by rigorous control of the process, lack of which may lead to premature failure. Over peening or shot peening a thin part at too high an intensity will lead to deformation, either mechanically due to the impingement of the shot, or by creating sub-surface tensile stresses too large to be supported by the component. If the shot peening operation does not treat the entire area properly, the desired fatigue resistance may not be demonstrated, leaving 'soft' spots where cracks may grow. Shot peening has a tendency to leave a dimpled orange peel finish at the surface. To retain a smooth finish the surface can be polished, honed or lapped provided that not more than 10 per cent of the depth of the induced compressive layer is removed.

Typical applications are the treatment of springs, gears, shafts and axles, and for post-weld treatment. These applications are reviewed briefly.

The forming operation required in the manufacture of springs tends to impart severe residual stresses, usually tensile, in the spring surface. Shot peening is an effective method of producing a desired residual compressive stress in a spring. The peening process is relatively inexpensive and has proved capable of increasing operating life by a factor of 5 or more, or increasing allowable operating stress for infinite life by a factor of 1.7 in the best cases. More information on springs can be obtained from Data Items Nos 80004^{*}, 83002[†] and 83003[‡] of the Stress and Strength Sub-series.

Field and laboratory tests have shown that the bending fatigue strength of gear teeth can be increased by a factor of at least 1.2 by shot peening. Shot peening can also play a part in increasing the surface fatigue life of gear teeth. High shear stresses at the surface of gear teeth cause small cracks beneath the surface to propagate outwards in a V-shape, causing a piece of metal to chip out of the surface, leaving a pit. The residual stress induced by shot peening at, and below, the material surface inhibits the formation and propagation of these cracks, and, as a consequence, extends the surface fatigue life.

Components subject to rotational bending which are prone to fatigue, such as shafts, axles, splines and fillets, can be shot peened at any change in cross-section with considerable benefit. Tests on axle shafts have indicated that peening can increase the fatigue strength by a factor of between 2 and 3. Induced compressive stress at the site of a stress concentration, such as a notch or change in section, will tend to nullify the effect of the stress concentration, and can lead to a complete restoration of the unnotched fatigue strength.

Welded assemblies suffer fatigue and stress corrosion cracking because of high residual tensile stresses and surface defects in the heat affected zone. Both shot peening and hammering have been successfully used to modify the effect of these tensile stresses, extending the fatigue life of the component by changing the geometry of a weld seam and producing large surface compressive residual stress. Welds on pressure vessels or welded structural parts have been treated successfully with shot peening techniques. Tests have shown that for high-strength structural steels, a factor of improvement in the fatigue strength of the welded joint of more than 2.5 can be obtained through correct peening. More information can be found in Data Items Nos 78016^{**} and 86013^{††}.

Shot peening can be used to form parts having single or double curvature and to correct distortions due to machining or heat treatment in materials of hardness up to HV 700. Peen forming has the effect of introducing compressive stresses into both faces of a component, thus generating the shape required with additional fatigue resistance benefits.

Components can be shot peened after suffering fatigue damage in order to rejuvenate parts that have

* Data Item No. 80004 "Fatigue strength of steel coned disc springs".

† Data Item No. 83002 "Allowable stresses for helical compression and tension springs of round wire".

‡ Data Item No. 83003 "Notes on the design of helical compression and tension springs of round wire".

** Data Item No. 78016 "The effect of post-weld treatments on fatigue at fillet welded attachments".

†† Data Item No. 86013 "Guide to the use of Data Items on the fatigue strength of welded joints in steels".

experienced a significant percentage of their fatigue life. The two mechanisms by which fatigue strength can be restored are the introduction of surface residual compressive stresses and the closure of any initiating sites or micro-cracks by plastic deformation of the surface. However, by the time a crack has grown to a practically detectable length it is unlikely that it will be possible to obliterate it by shot peening, and the latter mechanism is not applicable. Thus, peening to overwhelm micro-cracks and initiation sites can be done only as part of maintenance practice, carried out after a set percentage of expired life before any cracks become detectable. If, however, cracks are detected it is sometimes possible to machine or grind the surface to remove the crack, and then to peen the surface to restore fatigue strength. The introduction of residual stress is the more important mechanism of fatigue strength restoration. If a crack is small relative to the depth of the compressive residual stress field, the subsequent rate of crack growth is slowed. Section 3 explains this effect.

Peening can also be used to reintroduce compressive stresses that have been relaxed as a result of extreme loading conditions or environment met in service.

6. THERMAL TREATMENT

This section details the four main selective surface heat treatment processes currently used to improve the fatigue properties of steels, these being: (1) induction hardening; (2) flame hardening; (3) laser hardening; and (4) electron beam hardening.

Local surface heat treatments can be applied to plain carbon or low alloy steels and cast irons in the fully annealed, normalised or hardened and tempered conditions. This prior heat treatment of annealing, normalising, hardening and tempering not only develops the required mechanical properties for the core, but also controls the microstructure at the beginning of local surface heat treatment. For example, coarse annealed components do not respond to surface treatment having a short heating period as effectively as do normalised or hardened and tempered components. Steel selection is based on ability to provide the desired core strength in the component to be used, and the ability to attain the necessary case depth. Table 6.1 indicates standards that may be used for material selection.

TABLE 6.1

<i>Material</i>	<i>British Standard No.</i>
Wrought steels	BS 970
Cast steels	BS 3100
Pearlitic malleable irons	BS 3333
Spheroidal graphite irons	BS 2789

The principle of this process is the rapid application of heat to the surface of a component such that the core remains relatively cool. When the surface layers of a steel are heated rapidly to the austenising temperature, typically 850°C (1560°F) and above, they expand and are restrained by the cold core. As this temperature is very high in relation to that at which creep occurs in a low alloy steel, the surface layers accommodate plastically to the core. On quenching, the surface layers initially contract and then expand again when the austenitic structure is transformed to martensite. This expansion is constrained by the core, thus developing residual compressive stresses in the surface layers. These stresses improve the fatigue strength in the manner described in Section 3.

Tensile stresses are also developed at the case-to-core interface. Under bending loading the compressive layer must have sufficient depth to overcome the fatigue conditions imposed so that a fatigue failure does

not originate in this tensile stress region. In such cases it is therefore essential to ensure that the case depth is adequate to avoid fatigue failure of the core. Conversely it is important to ensure that too thick a case is not specified on small-section components as the residual tensile stress itself can increase to beyond the intrinsic fatigue limit of the core.

It should be noted that all heat treatments must be carried out fully and at the correct temperature, as any shortcoming will not only lead to poorer than expected fatigue performance but may lead to a fatigue performance lower than that of the untreated steel.

6.1 Induction Surface Treatment

Here heating is by electromagnetic induction. A conductor, which is coiled, has alternating current passed through it. This creates a magnetic flux within the coil which induces eddy currents in the surface layer of a metal component held within this field causing heat generation at the surface layer. The depth of penetration of the heated layer is governed mainly by the power and frequency employed. The depths of case produced by typical process conditions are from 0.5 to 5.0 mm (0.02 to 0.20 in).

There are two basic techniques for induction treatment of components, single-shot and scanning. The former employs selective heating and quenching to treat specific areas of a component in one operation, and the latter is usually applied to long, continuous sections such as shafts and spindles. In the latter the scanning inductor traverses the length of the section, heating only a relatively small area at any one time, and is followed closely by the quench arrangement.

In addition to improving the fatigue strength, induction hardening has the benefit of very short heating times without the use of a naked flame. This leads to minimum surface decarburisation and oxidation, small distortion, and good repeatability.

Induction hardening does have certain disadvantages. Only a limited number of grades of steel can be successfully treated. Below 0.35 per cent carbon the treated surface has negligible surface residual stress, and above 0.60 per cent carbon there is a danger of surface cracking. Components of axisymmetric shape only are suitable for treatment.

6.2 Flame Surface Treatment

Flame surface treatment is very similar to induction treatment, and gives very similar results. Compared to induction treatment, flame surface treatment is more costly to operate and less easily controlled. However, it requires less capital investment and there are fewer restrictions on the shape of components that can be treated.

Three main processes can be used.

- (a) 'Manual' or 'spot', in which the flame is directed at the area to be heated until the required temperature is obtained. The area is then quenched by immersion or in a spray.
- (b) 'Progressive', in which the flame is moved slowly over the surface and is followed by a quenching spray that may be attached to the burner head. This is suitable for large plates and long components.
- (c) 'Spinning', in which the component is rotated in the flame. This is applicable to axisymmetric or near axisymmetric parts such as gears and camshafts.

The depth of the residual stress layer is governed by the composition of the steel (mainly the carbon content), the temperature employed and the rate of cooling. For a given steel cooled at a certain rate the heating time

and intensity of heating are the decisive factors. Case depths of up to 5 mm (0.2 in) can be obtained. The depth of compressive stress is also a function of the burner distance from the work surface, a short burner distance resulting in a greater depth of effect.

Fuels used in the flame treatment process include acetylene, propane and natural gas, all of which can be burned in air or oxygen. The critical austenising temperature is reached much more rapidly with acetylene-oxygen than propane-oxygen or natural gas-oxygen, giving a much more sharply defined depth of case.

The advantages of flame heating are similar to those of induction hardening, with the major addition of its ease of use. For example, manual systems can be used on site. It can also be used to treat a much wider range of components including asymmetric shapes.

As with induction treatment, flame heating has the disadvantage that only a limited range of steels are treatable, that is steels having compositions in the range 0.35 to 0.60 per cent carbon. It has the added disadvantage that it is difficult to obtain consistent and uniform residual surface compressive stresses, and care is needed with complicated shapes to ensure no complementary tensile residual stresses exist at a free surface. Flame treatments also have the problem of oxidation or decarburisation at the steel surface, particularly if the steel is overheated or burned. At temperatures of around 1100°C (2000°F) under oxidising conditions, there is also the risk of any copper content in the steel melting, concentrating and diffusing between the grain boundaries, and leading to surface cracking.

6.3 Laser Transformation Treatment

Laser transformation is a solid state transformation technique that uses a fine focus high energy beam as the energy source. It is characterised by the fact that the surface of a ferrous material achieves the austenitisation temperature after a very short interaction time (a fraction of a second) whilst the bulk of the material remains unaffected. Consequently, on removal of the laser, there is no need for an external quenchant to bring about martensite transformation to create the desired residual compressive stress layer in the case, because the bulk of the material provides an adequate heat sink to cause self-quenching. For self-quenching the component thickness must be at least four times that of the case.

For this process the most widely used laser is the carbon dioxide (CO₂) laser, which operates at a wavelength of 16 µm. As clean metallic surfaces are poor absorbers of radiation at this wavelength (as much as 95 per cent of the incident energy being reflected), the surface must be prepared before treatment by coating with a non-reflective layer, for example, colloidal graphite.

Typically, laser treatment is employed where cases up to about 1 mm (0.04 in) deep are required, the depth of case being controlled by both time and the energy applied per unit of surface area. Deeper cases can be produced by reducing beam power density and increasing treatment time, but many of the advantages of the laser method are then lost. Owing to the short treatment times, as compared to flame and induction treatment, and the self-quenching aspect of the treatment, distortion is very low, even in thin components. Other advantages derive from the high controllability of the process, these include greater selectivity and precision of the area treated, ability to treat areas inaccessible to conventional techniques, good repeatability and flexibility.

Since treatment cycles are extremely short, alloy irons and steels containing elements that reduce the critical cooling rate for transformation from the austenitising temperature, and ferrous materials that readily austenitise, are those materials best suited to laser transformation treatment. However, because the laser process is very localised and can result in extremely rapid cooling rates, very low carbon steels (0.2 per cent carbon) can be treated.

6.4 Electron Beam Transformation Treatment

This process is very similar to laser treatment but using an electron beam as the energy source. It relies on the transformation of the surface layer of a steel to produce compressive residual stresses. The main disadvantage of electron beam treatment is the requirement to operate in a vacuum. However, a vacuum provides excellent environmental protection for a heat treated surface. As electrons have low inertia it is possible to control the beam very easily by electromagnetic forces. By using a computer to control the operating parameters of the electron beam, the beam shape and density and the cooling rate of the process can be altered to control the distribution of heat energy to the work surface. Thus it becomes possible to treat complex surface geometries, including components requiring a variable case depth.

Electron beam treatment is more flexible than laser treatment because the energy is easily distributed over the workpiece and is not limited by the mirror deflection capabilities as it is with lasers. Further, obtaining the required energy distribution using a laser beam directed by electromechanically operated mirrors is difficult since the system is susceptible to vibration. The electron beam method is much more energy efficient than the laser method, and has lower capital and operating costs.

The depth of the heat treated layer can be from 0.2 to 2.5 mm (0.008 to 0.1 in), with the most advantageous results in the range 0.75 to 1 mm (0.03 to 0.04 in). For self-quenching the thickness of the part must be at least four times that of the heat treated layer in order to provide a sufficient heat sink.

Compared with flame and induction treatment processes electron beam heat treatment has the advantage of low distortion, cleanliness, reliability, reproducibility and flexibility. It does have the disadvantage of cost and the necessity to operate in vacuum.

7. THERMO-CHEMICAL TREATMENTS

In this category of treatment the surface chemistry of a steel is modified by the introduction of carbon and/or nitrogen, and in some treatments other elements, at elevated temperatures. Thermo-chemical processes may be subdivided into the following main groups: carburising; carbonitriding; nitriding; and ferritic nitrocarburising.

Various media can be used for thermo-chemical treatments. These are used to broadly classify the processes involved, and are as follows.

- (1) Gaseous processes (such as gas carburising, gas nitriding).
- (2) Salt-bath processes (such as salt-bath carbonitriding).
- (3) Vacuum processes (such as vacuum carburising, ion and plasma nitriding).
- (4) Pack processes (such as carburising in activated carbonaceous material).

Gaseous thermo-chemical treatments are by far the most widely used as they are particularly suitable for continuous operation, whereas the other processes are batch production orientated. They are also generally cheaper to operate than liquid salt baths which can present environmental and component cleaning problems. Equipment for gaseous treatments is available in larger capacity units than salt baths, and the process provides more versatility in that a change from one process to another may involve only a change in gas composition and operating temperature. Vacuum processes, in particular plasma nitriding, have grown in importance in recent years and are becoming much more widely available.