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IACS UR M53, Appendix V

Guidance for calculation of

Surface Treated Fillets and Oil Bore Outlets

Index

1. Introduction

This appendix deals with surface treated fillets and oil bore outlets. The various treatments are explained and some empirical formulae are given for calculation purposes. Conservative empiricism has been applied intentionally, in order to be on the safe side from a calculation standpoint.

Please note that measurements or more specific knowledge should be used if available. However, in the case of a wide scatter (e.g. for residual stresses) the values should be chosen from the end of the range that would be on the safe side for calculation purposes.

2. Definition of surface treatment

'Surface treatment' is a term covering treatments such as thermal, chemical or mechanical operations, leading to inhomogeneous material properties – such as hardness, chemistry or residual stresses – from the surface to the core.

2.1. Surface treatment methods

The following list covers possible treatment methods and how they influence the properties that are decisive for the fatigue strength.

Table 2.1. Surface treatment methods and the characteristics they affect.

Treatment method	Affecting
• Induction hardening	Hardness and residual stresses
• Nitriding	Chemistry, hardness and residual stresses
• Case hardening	Chemistry, hardness and residual stresses
• Die quenching (no temper)	Hardness and residual stresses
• Cold rolling	Residual stresses
• Stroke peening	Residual stresses
• Shot peening	Residual stresses
• Laser peening	Residual stresses
• Ball coining	Residual stresses

It is important to note that since only induction hardening, nitriding, cold rolling and stroke peening are considered relevant for marine engines, other methods are not dealt within this document. In addition die quenching can be considered in the same way as induction hardening.

3. Calculation principles

The basic principle is that the alternating working stresses shall be below the local fatigue strength (including the effect of surface treatment) wherein non-propagating cracks may occur, see also section 6.1 for details. This is then divided by a certain safety factor. This applies through the entire fillet or oil bore contour as well as below the surface to a depth below the treatment-affected zone – i.e. to cover the depth all the way to the core.

Consideration of the local fatigue strength shall include the influence of the local hardness, residual stress and mean working stress. The influence of the 'giga-cycle effect', especially for initiation of subsurface cracks, should be covered by the choice of safety margin.

It is of vital importance that the extension of hardening/peening in an area with concentrated stresses be duly considered. Any transition where the hardening/peening is ended is likely to have considerable tensile residual stresses. This forms a 'weak spot' and is important if it coincides with an area of high stresses.

Alternating and mean working stresses must be known for the entire area of the stress concentration as well as to a depth of about 1.2 times the depth of the treatment. The following figure indicates this principle in the case of induction hardening. The base axis is either the depth (perpendicular to the surface) or along the fillet contour.

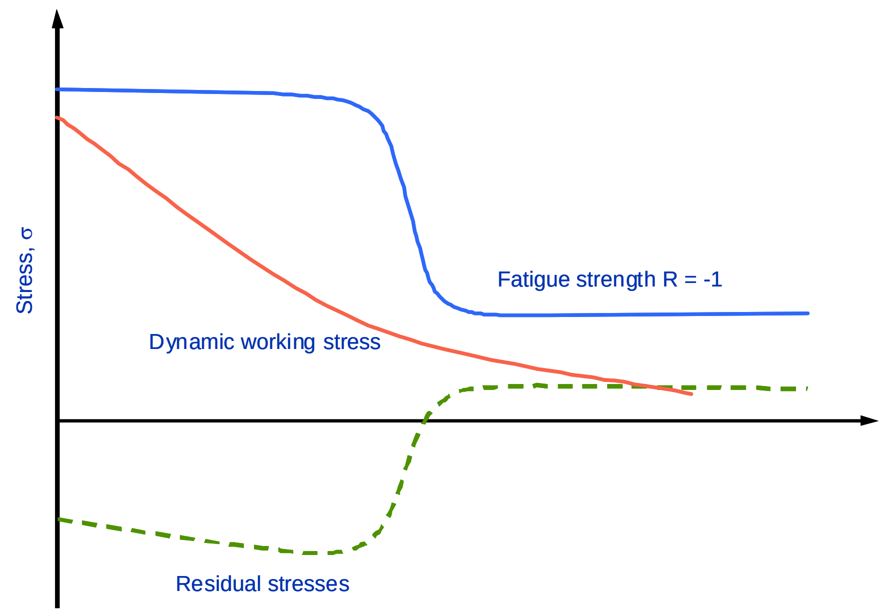


Figure 3.1. Stresses as functions of depth, general principles.

The acceptability criterion is to be applied stepwise from the surface to the core as well as from the point of maximum stress concentration along the fillet surface contour to the web.

3.1. Evaluation of local fillet stresses

It is necessary to have knowledge of the stresses along the fillet contour as well as in the subsurface to a depth somewhat beyond the hardened layer. Normally this will be found via FEA as described in Appendix III. However, the element size in the subsurface range will have to be the same size as at the surface. For crankpin hardening only the small element size will have to be continued along the surface to the hard layer.

If no FEA is available, a simplified approach may be used. This can be based on the empirically determined stress concentration factors (SCFs), as in M53.3 if within its validity range, and a relative stress gradient inversely proportional to the fillet radius. Bending and torsional stresses must be addressed separately. The combination of these is addressed by the acceptability criterion.

The subsurface transition-zone stresses, with the minimum hardening depth, can be determined by means of local stress concentration factors along an axis perpendicular to the fillet surface. These functions $\alpha_{B\text{-}local}$ and $\alpha_{T\text{-}local}$ have different shapes due to the different stress gradients.

The SCFs α_B and α_T are valid at the surface. The local $\alpha_{B\text{-}local}$ and $\alpha_{T\text{-}local}$ drop with increasing depth. The relative stress gradients at the surface depend on the kind of stress raiser, but for crankpin fillets they can be simplified to $2/R_H$ in bending and $1/R_H$ in torsion. The journal fillets are handled analogously by using R_G. The nominal stresses are assumed to be linear from the surface to a midpoint in the web between the crankpin fillet and the journal fillet for bending and to the crankpin or journal centre for torsion.

The local SCFs are then functions of depth t according to Equation 3.1 as shown in Figure 3.2 for bending and respectively for torsion in Equation 3.2 and Figure 3.3.

$$\alpha_{B-local} = (\alpha_B - 1) \cdot e^{\frac{-2 \cdot t}{R_H}} + 1 - \left(\frac{2 \cdot t}{\sqrt{W^2 + S^2}} \right)^{\frac{0.6}{\sqrt{\alpha_B}}} \tag{3.1}$$

$$\alpha_{T-local} = (\alpha_T - 1) \cdot e^{\frac{-t}{R_H}} + 1 - \left(\frac{2 \cdot t}{D} \right)^{\frac{1}{\sqrt{\alpha_T}}} \tag{3.2}$$

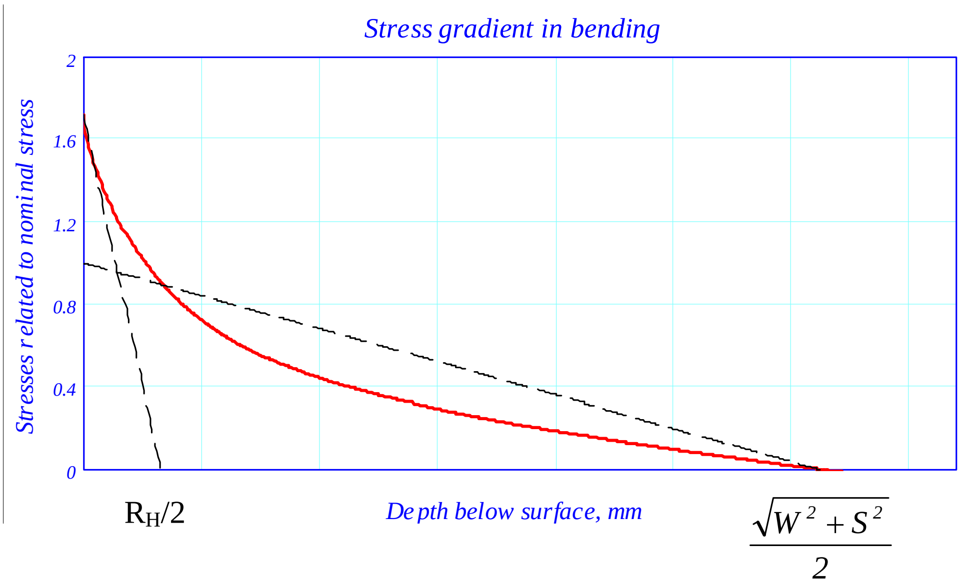


Figure 3.2. Bending SCF in the crankpin fillet as a function of depth. The corresponding SCF for the journal fillet can be found by replacing R_H with R_G.

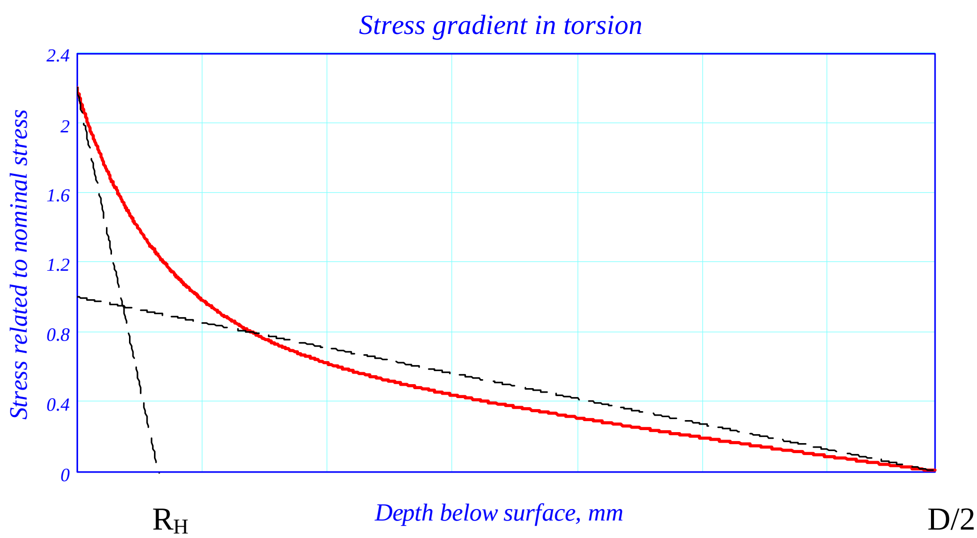


Figure 3.3. Torsional SCF in the crankpin fillet as a function of depth. The corresponding SCF for the journal fillet can be found by replacing R_H with R_G and D with D_G.

If the pin is hardened only and the end of the hardened zone is closer to the fillet than three times the maximum hardness depth, FEA should be used to determine the actual stresses in the transition zone.

3.2. Evaluation of oil bore stresses

Stresses in the oil bores can be determined also by FEA. The element size should be less than 1/8 of the oil bore diameter D_O and the element mesh quality criteria should be followed as prescribed in Appendix III. The fine element mesh should continue well beyond a radial depth corresponding to the hardening depth.

The loads to be applied in the FEA are the torque – see Appendix III item 3.1 – and the bending moment, with four-point bending as in Appendix III item 3.2.

If no FEA is available, a simplified approach may be used. This can be based on the empirically determined SCF from M53.3 if within its applicability range. Bending and torsional stresses at the point of peak stresses are combined as in M53.5.

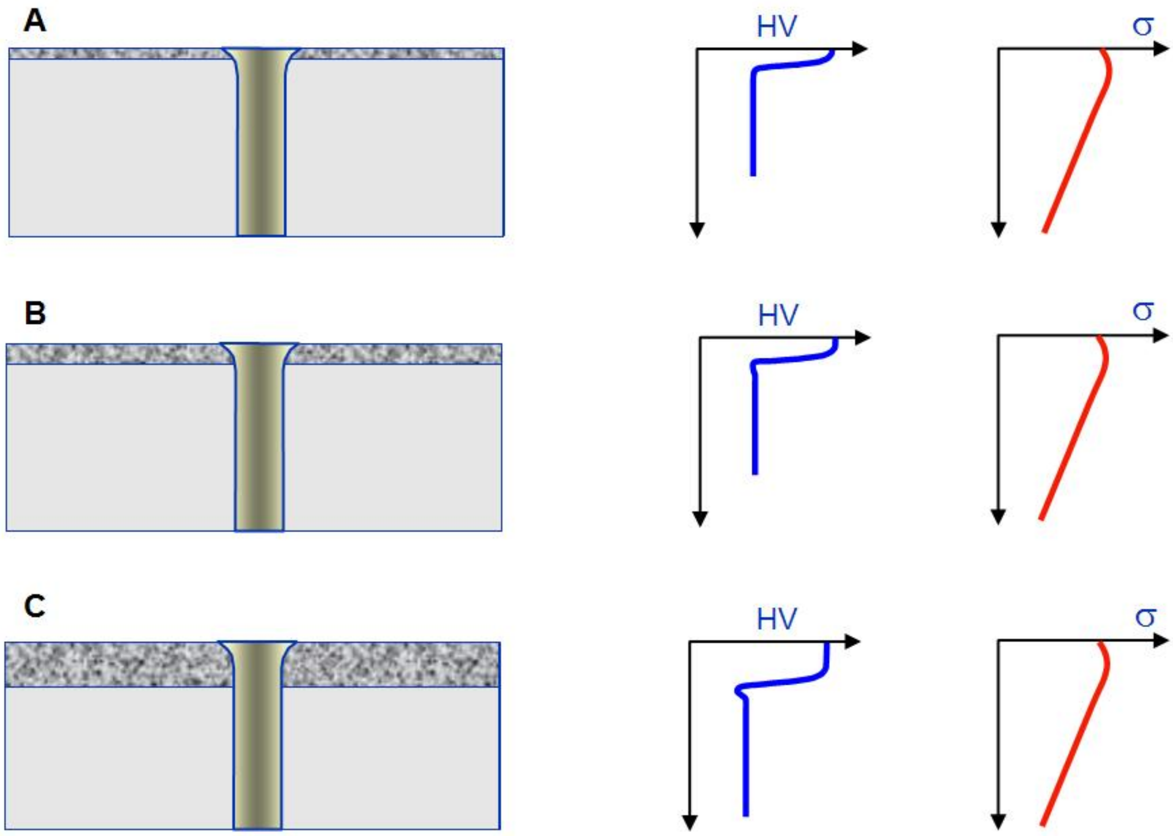


Figure 3.4. Stresses and hardness in induction hardened oil holes.

Figure 3.4 indicates a local drop of the hardness in the transition zone between a hard and soft material. Whether this drop occurs depends also on the tempering temperature after quenching in the QT process.

The peak stress in the bore occurs at the end of the edge rounding. Within this zone the stress drops almost linearly to the centre of the pin. As can be seen from Figure 3.4, for shallow (A) and intermediate (B) hardening, the transition point practically coincides with the point of maximal stresses. For deep hardening the transition point comes outside of the point of peak stress and the local stress can be assessed as a portion $(1\text{-}2{\cdot}t_H/D)$ of the peak stresses where t_H is the hardening depth.

The subsurface transition-zone stresses (using the minimum hardening depth) can be determined by means of local stress concentration factors along an axis perpendicular to the oil bore surface. These functions $\gamma_{B\text{-}local}$ and $\gamma_{T\text{-}local}$ have different shapes, because of the different stress gradients.

The stress concentration factors γ_B and γ_T are valid at the surface. The local SCFs $\gamma_{B\text{-}local}$ and $\gamma_{T\text{-}local}$ drop with increasing depth. The relative stress gradients at the surface depend on the kind of stress raiser, but for crankpin oil bores they can be simplified to $4/D_O$ in bending and $2/D_O$ in torsion. The local SCFs are then functions of the depth t:

$$\gamma_{B-local} = (\gamma_B - 1) \cdot e^{\frac{-4 \cdot t}{D_O}} + 1 \tag{3.3}$$

$$\gamma_{T-local} = (\gamma_T - 1) \cdot e^{\frac{-2 \cdot t}{D_O}} + 1 \tag{3.4}$$

3.3. Acceptability criteria

Acceptance of crankshafts is based on fatigue considerations; M53 compares the equivalent alternating stress and the fatigue strength ratio to an acceptability factor of $Q \geq 1.15$ for oil bore outlets, crankpin fillets and journal fillets. The term ‘safety factor’ is intentionally not used, since the method contains several so-called hidden safeties.

Table 3.1. Some assumptions leading to so-called hidden safety.

I. Analytical equations do not cover complicated crank web geometries or fillet shapes
II. Three-point bending applies on one crankthrow without influence from adjacent cranks
III. Full torque applies on the crankpin, i.e. no restraint in main bearings is included
IV. Stress concentration for torsion and bending occurs at the same location in a fillet
V. Maximum torsion and maximum bending stresses are in phase
VI. Fatigue strength is assessed without the influence of mean stress

For calculations assuming I-III, even if SCFs are found by FEA, the acceptability factor of 1.15 should remain. When more accurate calculations are made (e.g. when one or more of the hidden safeties are bypassed) the acceptability factor turns more toward the safety factor and a suitable value and approach should be applied.

4. Induction hardening

Generally the hardness specification shall specify the surface hardness range i.e. minimum and maximum values, the minimum and maximum extension in or through the fillet and also the minimum and maximum depth along the fillet contour.

The induction hardening depth is defined as the depth where the hardness is 80% of the minimum specified surface hardness.

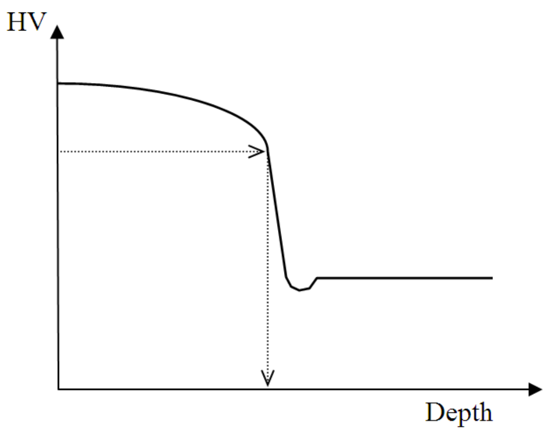


Figure 4.1. Typical hardness as a function of depth. The arrows indicate the defined hardening depth. Note the indicated potential hardness drop at the transition to the core. This can be a weak point as local strength may be reduced and tensile residual stresses may occur.

In the case of crankpin or journal hardening only, the minimum distance to the fillet shall be specified due to the tensile stress at the heat-affected zone as shown in Figure 4.2.

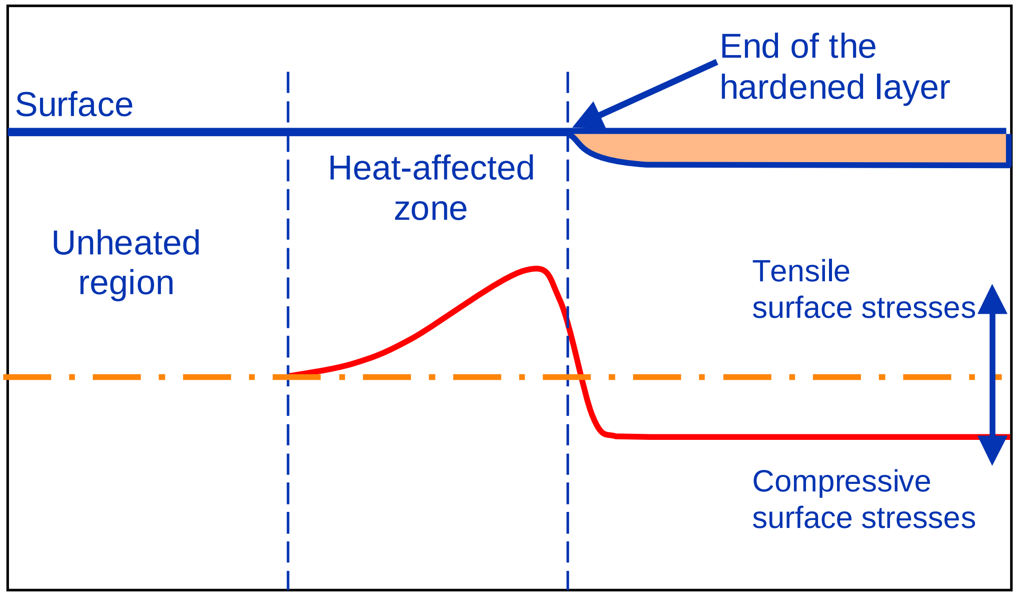


Figure 4.2. Residual stresses along the surface of a pin and fillet.

If the hardness-versus-depth profile and residual stresses are not known or specified, one may assume the following:

- The hardness profile consists of two layers (see figure 4.1):
    - Constant hardness from the surface to the transition zone
    - Constant hardness from the transition zone to the core material
- Residual stresses in the hard zone of 200 MPa (compression)
- Transition-zone hardness as 90% of the core hardness unless the local hardness drop is avoided
- Transition-zone maximum residual stresses (von Mises) of 300 MPa tension

If the crankpin or journal hardening ends close to the fillet, the influence of tensile residual stresses has to be considered. If the minimum distance between the end of the hardening and the beginning of the fillet is more than 3 times the maximum hardening depth, the influence may be disregarded.

4.1. Local fatigue strength

Induction-hardened crankshafts will suffer fatigue either at the surface or at the transition to the core. The fatigue strengths, for both the surface and the transition zone, can be determined by fatigue testing of full size cranks as described in Appendix IV. In the case of a transition zone, the initiation of the fatigue can be either subsurface (i.e. below the hard layer) or at the surface where the hardening ends. Tests made with the core material only will not be representative since the tensile residual stresses at the transition are lacking.

Alternatively, the surface fatigue strength (principal stress) can be determined empirically as follows where *HV* is the surface (Vickers) hardness. The Equation 4.1 provides a conservative value, with which the fatigue strength is assumed to include the influence of the residual stress. The resulting value is valid for a working stress ratio of *R* = -1:

$$\sigma_{Fsurface} = 400 + 0.5 \cdot (HV - 400) \qquad [MPa] \qquad (4.1)$$

It has to be noted also that the mean stress influence of induction-hardened steels may be significantly higher than that for QT steels.

The fatigue strength in the transition zone, without taking into account any possible local hardness drop, shall be determined by the equation introduced in UR M53.6. For journal and respectively to crankpin fillet applies:

$$\sigma_{Ftransition,cpin} = \pm K \cdot (0.42 \cdot \sigma_B + 39.3) \cdot \left[0.264 + 1.073 \cdot Y^{-0.2} + \frac{785 - \sigma_B}{4900} + \frac{196}{\sigma_B} \cdot \sqrt{\frac{1}{X}} \right] \qquad (4.2)$$

Where

$Y = D_G$ and $X = R_G$ for journal fillet
$Y = D$ and $X = R_H$ for crankpin fillet

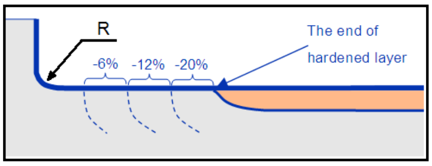
The influence of the residual stress is not included in 4.2.

For the purpose of considering subsurface fatigue, below the hard layer, the disadvantage of tensile residual stresses has to be considered by subtracting 20*%* from the value determined above. This 20*%* is based on the mean stress influence of alloyed quenched and tempered steel having a residual tensile stress of 300 *MPa*. When the residual stresses are known to be lower, also smaller value of subtraction shall be used. For low-strength steels the percentage chosen should be higher.

For the purpose of considering surface fatigue near the end of the hardened zone – i.e. in the heat-affected zone shown in the Figure 4.2 – the influence of the tensile residual stresses can be considered by subtracting a certain percentage, in accordance with Table 4.1, from the value determined by the above formula.

Table 4.1. The influence of tensile residual stresses at a given distance from the end of the hardening.

I. 0 to 1.0 of the max. hardening depth: 20%
II. 1.0 to 2.0 of the max. hardening depth: 12%
III. 2.0 to 3.0 of the max. hardening depth: 6%
IV. 3.0 or more of the max. hardening depth: 0%



5. Nitriding

The hardness specification shall include the surface hardness range (min and max) and the minimum and maximum depth. Only gas nitriding is considered.

The depth of the hardening is defined in different ways in the various standards and the literature. The most practical method to use in this context is to define the nitriding depth t_N as the depth to a hardness of 50 *HV* above the core hardness.

The hardening profile should be specified all the way to the core. If this is not known, it may be determined empirically via the following formula:

$$HV(t) = HV_{core} + (HV_{surface} - HV_{core}) \cdot \left(\frac{50}{HV_{surface} - HV_{core}} \right)^{\left(\frac{t}{t_N}\right)^2} \qquad (5.1)$$

Where:

t	=	The local depth
$HV(t)$	=	Hardness at depth t
HV_{core}	=	Core hardness
$HV_{surface}$	=	Surface hardness
t_N	=	Nitriding depth as defined above

5.1. Local fatigue strength

It is important to note that in nitrided crankshaft cases, fatigue is found either at the surface or at the transition to the core. This means that the fatigue strength can be determined by tests as described in Appendix IV.

Alternatively, the surface fatigue strength (principal stress) can be determined empirically and conservatively as follows. This is valid for a surface hardness of 600*HV* or greater:

$$\sigma_{Fsurface} = 450MPa \tag{5.2}$$

Note that this fatigue strength is assumed to include the influence of the surface residual stress and applies for a working stress ratio of R = -1.

The fatigue strength in the transition zone can be determined by the equation introduced in UR M53.6. For crankpin and respectively to journal applies:

$$\sigma_{Ftransition,cpin} = \pm K \cdot (0.42 \cdot \sigma_B + 39.3) \cdot \left[0.264 + 1.073 \cdot Y^{-0.2} + \frac{785 - \sigma_B}{4900} + \frac{196}{\sigma_B} \cdot \sqrt{\frac{1}{X}} \right] \tag{5.3}$$

Where

$Y = D_G$ and $X = R_G$ for journal fillet
$Y = D$ and $X = R_H$ for crankpin fillet

Note that this fatigue strength is **not** assumed to include the influence of the residual stresses.

In contrast to induction-hardening the nitrited components have no such distinct transition to the core. Although the compressive residual stresses at the surface are high, the balancing tensile stresses in the core are moderate because of the shallow depth. For the purpose of analysis of subsurface fatigue the disadvantage of tensile residual stresses in and below the transition zone may be even disregarded in view of this smooth contour of a nitriding hardness profile.

Nevertheless, in principle the calculation should be carried out along the entire hardness profile and it can be limited to a simplified approach of examining the surface and an artificial transition point. This artificial transition point can be taken at the depth where the local hardness is approximately 20 *HV* above the core hardness. In such a case, the properties of the core material should be used. This means that the stresses at the transition to the core can be found by using the local SCF formulae mentioned earlier when inserting t=1.2·t_N.

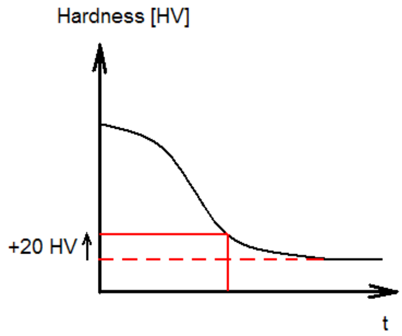


Figure 5.1. Sketch of the location for the artificial transition point in the depth direction.

6. Cold forming

The advantage of stroke peening or cold rolling of fillets is the compressive residual stresses introduced in the high-loaded area. Even though surface residual stresses can be determined by X-ray diffraction technique and subsurface residual stresses can be determined through neutron diffraction, the local fatigue strength is virtually non-assessable on that basis since suitable and reliable correlation formulae are hardly known.

Therefore the fatigue strength has to be determined by fatigue testing; see also Appendix IV. Such testing is normally carried out as four-point bending, with a working stress ratio of R = -1. From these results the bending fatigue strength – surface- or subsurface-initiated depending on the manner of failure – can be determined and expressed as the representative fatigue strength for applied bending in the fillet.

In comparison to bending, the torsion fatigue strength in the fillet may differ considerably from the ratio √3 (utilized by the von Mises criterion). The forming-affected depth that is sufficient to prevent subsurface fatigue in bending, may still allow subsurface fatigue in torsion. Another possible reason for the difference in bending and torsion could be the extension of the highly stressed area.

The results obtained in a full size crank test can be applied for another crank size provided that the base material (alloyed Q+T) is of the same type and that the forming is done so as to obtain the same level of compressive residual stresses at the surface as well as through the depth. This means that both the extension and the depth of the cold forming must be proportional to the fillet radius.

6.1. Stroke peening by means of a ball

The fatigue strength obtained can be documented by means of full size crank tests or by empirical methods if applied on the safe side. If both bending and torsion fatigue strengths have been investigated and differ from the ratio √3, the von Mises criterion should be excluded.

If only bending fatigue strength has been investigated, the torsional fatigue strength should be assessed conservatively. If the bending fatigue strength is concluded to be x% above the fatigue strength of the non-peened material, the torsional fatigue strength should not be assumed to be more than 2/3 of x% above that of the non-peened material.

As a result of the stroke peening process the maximum of the compressive residual stress is found in the subsurface area. Therefore, depending on the fatigue testing load and the stress gradient, it is possible to have higher working stresses at the surface in comparison to the local fatigue strength of the surface. Because of this phenomenon small cracks may appear during the fatigue testing, which will not be able to propagate in further load cycles and/or with further slight increases of the testing load because of the profile of the compressive residual stress. Put simply, the high compressive residual stresses below the surface ‘arrest’ small surface cracks. This is illustrated in Figure 6.1 as gradient load 2.

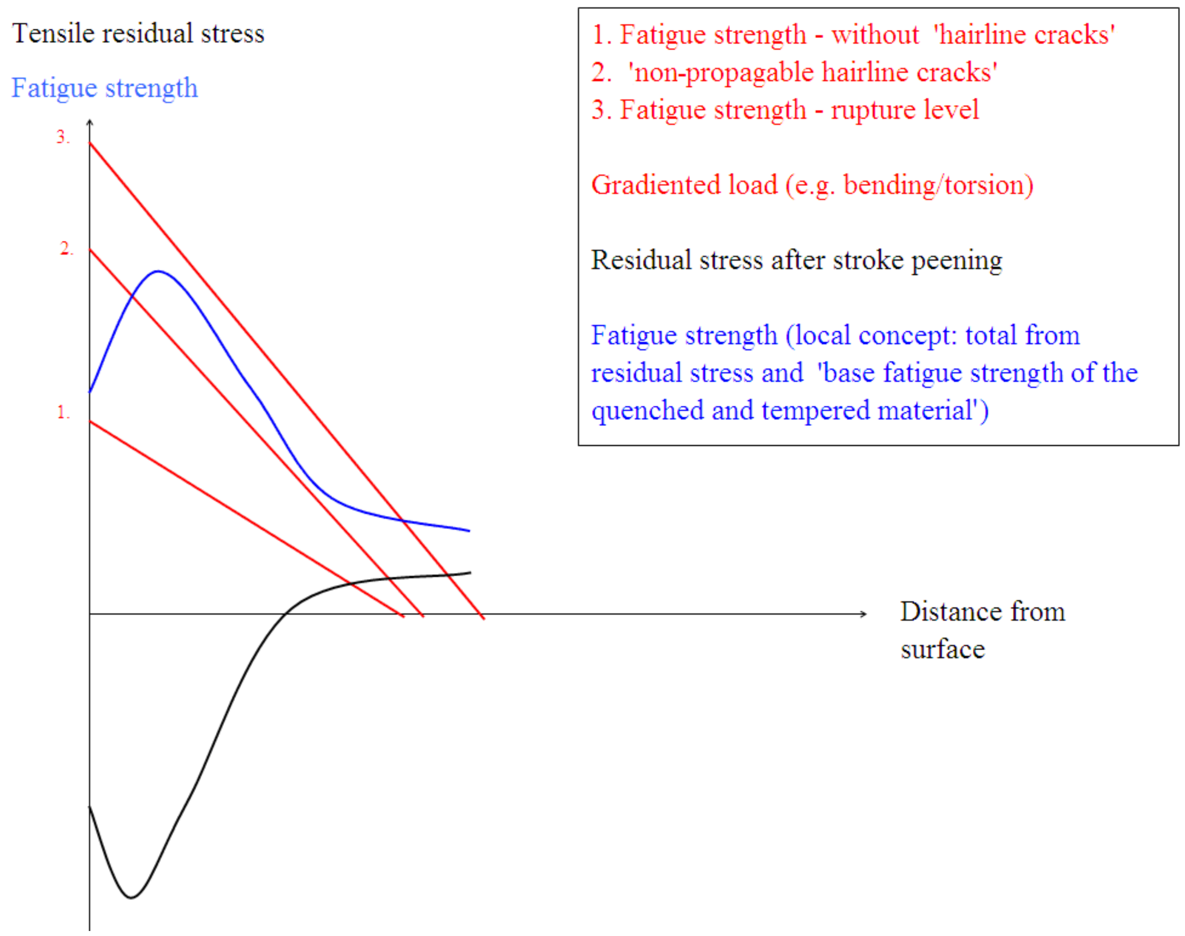


Figure 6.1. Working and residual stresses below the stroke-peened surface. Straight lines 1…3 represent different possible load stress gradients.

In fatigue testing with full-size crankshafts these small “hairline cracks” should not be considered to be the failure crack. The crack that is technically the fatigue crack leading to failure, and that therefore shuts off the test-bench, should be considered for determination of the failure load level. This also applies if induction-hardened fillets are stroke-peened.

In order to improve the fatigue strength of induction-hardened fillets it is possible to apply the stroke peening process in the crankshafts' fillets after they have been induction-hardened and tempered to the required surface hardness. If this is done, it might be necessary to adapt the stroke peening force to the hardness of the surface layer and not to the tensile strength of the base material. The effect on the fatigue strength of induction hardening and stroke peening the fillets shall be determined by a full size crankshaft test. See Appendix IV.

Fatigue results from tests on one crankshaft may be used for a similar crankshaft if all of the following criteria are fulfilled:

- Ball size relative to fillet radius within 90 ± 5%
- At least the same circumferential extension of the stroke peening
- At least the same angular extension of fillet contour stroke-peened
- Similar base material, e.g. alloyed quenched and tempered
- Forward feed of ball of the same proportion of the radius
- Force applied to ball proportional to base material hardness (if different)
- Force applied to ball proportional to square of ball radius

6.2. Cold rolling

The fatigue strength can be obtained by means of full size crank tests or by empirical methods if these are applied so as to be on the safe side. If both bending and torsion fatigue strengths have been investigated, and differ from the ratio $\sqrt{3}$, the von Mises criterion should be excluded.

If only bending fatigue strength has been investigated, the torsional fatigue strength should be assessed conservatively. If the bending fatigue strength is concluded to be x% above the fatigue strength of the non-rolled material, the torsional fatigue strength should not be assumed to be more than 2/3 of x% above that of the non-rolled material.

Fatigue test results from testing of a crankshaft may be applied to another crankshaft if that crankshaft is similar and all of the following criteria are fulfilled:

- At least the same circumferential extension of cold rolling
- At least the same angular extension of fillet contour rolled
- Similar base material, e.g. alloyed quenched and tempered
- Roller force to be calculated so as to achieve at least the same relative (to fillet radius) depth of treatment