Shot Peening Effects on Fatigue Life

A. Plumtree
University of Waterloo, Waterloo, Canada
E-mail: plumtree@uwaterloo.ca

Abstract

Smooth specimens were tested under reversed push-pull conditions (stress ratio R= minimum/maximum stress = -1) to examine the effect of shot peening on their fatigue behaviour. In order to give a broad range of application of the forged steels used for connecting rods, one was formed by the powder metallurgical process. The steels were tested in the original normalized as well as shot peened conditions.

Shot peening had little effect on the fatigue limit stress of these steels. It was apparent that shot peening produced a gradient of residual compressive stresses that was greater than that of the loading stresses. As a consequence, the anticipated beneficial effect on fatigue life was suppressed. It is suggested that the work hardening caused by shot peening was more beneficial in improving the fatigue strength than the accompanying induced residual compressive stresses.

1. Introduction

Automotive products must meet increasingly higher quality requirements while production time becomes shorter. New precision forging processes and innovative equipment are needed to achieve these results. Connecting rods for automotive applications are now typically manufactured by forging from either powder metals or air cooled microalloy steels. The traditional quench and tempered wrought forgings are being replaced where possible. Machinability of the wrought microalloy ferritic/pearlitic steels is generally better than the quenched and tempered steels, although mechanical properties such as fatigue and impact strengths could suffer. However, under similar operating conditions they may perform better than powdered metal forgings.

The use of powder metals has the advantage of producing near net-shape components, thus reducing material waste. Unfortunately, the cost of the process is relatively high due to both the material and more sophisticated manufacturing costs. However this process has allowed the introduction of innovative one piece “crackable” automotive connecting rods to be made, designed to be broken (or fracture split) at the big end to facilitate assembly. Before the introduction of these crackable steels, all connecting rod cap ends were manufactured separately to facilitate inclusion of the bearing and subsequent attachment to the crankshaft. The advantages of using crackable steels are that the costs to separate the cap end are lower and that the broken surfaces mate accurately when reassembled. Subsequently, the tolerances on the cap end internal diameter are closer. These advantages can be achieved by using crackable higher carbon (ie.C70) steel forgings which show a cleavage fracture surface similar to that of the powder forged components but are much cheaper to manufacture. However, since the fatigue resistance cannot be compromised, and one of the aims of this work is to investigate the performance of this steel under long periods (eg.N~10^7cycles) of small amplitude cyclic loading.

Shot peening is generally used to improve the fatigue performance of engineering components. In this case residual compressive stresses are induced in the surface layers. Concomitantly, work hardening takes place. Also, the accompanying surface roughness may initiate undesirable cracking which may be countered by the residual compressive stresses. However, these stresses can fade during cycling with the surface stress concentrations becoming more dominant than the residual stress field, allowing the fatigue cracks to initiate and subsequently propagate.

The object of this investigation is to assess the high cycle fatigue properties related to the manufacturing processes, including shot peening of steels used in the production of automotive connecting rods.

2. Materials and Experimental Procedure

The chemical analyses of the steels used in this investigation are given in Table 1 below.

Table I.
Chemical Analyses (%)

Steel	C	Mn	S	P	Si	Cu	Cr	Mo	Ni	V
1141 V	0.39	1.41	0.12	0.01	0.24	0.05	0.10	0.01	0.03	0.06
PF*	0.50	-	-	-	-	1.5	-	0.4	-	-
C70 S6	0.70	0.55	-	0.02	0.15	-	0.15	-	-	0.02

* Density of the PF (powder forged) sample = 7.7grm/cm^3.

All the test specimens were normalized then machined in a flat dog-bone shape from automotive connecting rods of the compositions given in Table I. The specimen gauge width was 11.5 mm and thickness of 1.8mm. The length was 180 mm with a generous radius of 20 mm leading to the gripped ends. The as-machined surface roughness profile was 0.26 ± 0.03μm, measured using a Talysurf.

The steels were then divided into two groups. One group remained in the normalized (non-peened) condition. The other was shot peened using 1mm diameter steel shot, Almen scale 14-18A. The resulting surface roughness profile was measured and found to be 3.60 ± 0.44 μm.

X-ray diffraction profiles for all three steels after shot peening were found to be very similar. The surface stress was determined to be -375 MPa, with the maximum of -445 MPa at a depth of 0.10mm below the surface. The compressive layer extended to a depth of 0.65mm, i.e. where the compressive residual stress decreased to zero.

The initial hardness values of the steels were similar i.e. for 1141V, BHN 240±6; for PF, BHN 242±5 and for C70S6, BHN 251±4.

The specimens were fatigued tested in an Amsler Vibraphore machine under push-pull (R= minimum/maximum stress = -1) to) conditions, operating at a frequency of 150 Hz.

3. Results and Discussion

The mechanical properties of the three steels are given in Table II below.

Table II Mechanical Properties				
Steel	Yield Stress MPa	Tensile Strength MPa	Elongation %	Reduction of Area %
1141V	576	862	17	39
PF	570	906	14	30
C70S6	564	999	14	27

The fatigue limit stresses with standard deviations after 10^7 cycles are given in Table 3 below for the non-peened and peened steels.

TABLE 3 Fatigue Limits of Non-peened and Peened Steels R= -1		
Steel	Non-peened MPa	Peened MPa
1141V	324±5	332± 3
PF	311±20	343±22
C70S6	348 ± 6	341 ± 7

In general, the effect of shot peening was small, ranging from a decrease in the fatigue limit stress of -2.0% to an increase of 10.3%. The results showed that shot peening the wrought 1141V and C70S6 steels had very little effect (2.5% and - 2.0% respectively) on their fatigue limit stresses.

For the powder forged, PF, steel, shot peening was slightly beneficial yet the standard deviation was relatively high. The increase of 10.3% was small, especially when compared to that of about 22% reported after shot peening heat treated AISI 1045 steel (BHN 270) under reversed bending conditions [1]. It is interesting to point out that the reported increase was restricted to small amplitudes, hence long lives in the range of 10^7 cycles. For the shorter lives at higher stresses shot peening had little effect on the bending fatigue strength.

For shot peened material cycled under reversed loading conditions close to the fatigue limit, the stress amplitudes exceed the local fatigue strength below the surface because of shallow stress gradients. As a result, cracks tend to initiate below the surface.

When compared to bending fatigue, it should be noted that the loading stress gradients are shallower for the push-pull fatigue tests carried out on the three steel specimens in the present work. The gradient of the compressive residual stresses becomes much steeper than the gradient of the loading stresses. Consequently crack initiation should occur below the surface, avoiding the detrimental effect of surface roughness. When fatigue crack initiation takes place in these sub-surface regions, the detrimental effects of the rough shot peened surface fatigue life may not be apparent, as in the present work (3.60 ± 0.44 μm on compared to 0.26 ± 0.03μm in the present work)

Only small increases in the local fatigue strengths result near the surface because of the relatively small amounts of compressive residual stresses produced by shot peening. In addition, the local fatigue strengths are reduced further by relaxation of these compressive residual stresses, particularly during the long periods of cycling associated with the fatigue limit stress.

It is significant that relaxation of the residual stresses occurs quickly (during the first cycle according to Gucchichi and Castex [2]) due to the adjustment and rebalancing of these stresses caused by the plastic strain. Following their studies on heat treated (BHN 320) medium carbon (0.37% C) low alloy steel (4.5% Ni, 1.8% Cr, 0.51% Mo) Gucchichi and Castex showed that the residual stress became stable when the superposition of the stress remained below the cyclic yield stress. They reported that up to 10^3 cycles, the residual stress showed no significant relaxation in a quenched and tempered shot peened alloy steel. In another case, Eifler et.al.[3] showed that for a quench and tempered AISI 4140 steel (BHN 210) cyclic softening occurred sooner in the shot peened condition and that higher plastic strain amplitudes occurred in the shot peened samples. This showed that a significant amount of stress relaxation occurred earlier during the cycling of the shot peened steel, as compared to the non peened material.

Guechichi and Castex [2] showed that shot peening increased the tension-compression fatigue limit stress by 12% - comparable to that observed in the present work- and concluded that the effect on the fatigue strength of residual stress due to shot peening was negligible. They claimed that the improvement was due to the cold working caused by the peening, demonstrating that the effect of plastic deformation was more significant. Using this concept, they presented a model to predict the fatigue limit stresses of shot peened steel and showed good agreement with the experimental data. It is interesting to note that the model was based on the initiation of fatigue cracks in the subsurface layers, implying that the surface roughening caused by shot peening was of lesser importance. This is in agreement with Wang et.al. [4] who demonstrated that the fatigue limit of shot peened steels could be predicted based on the local fatigue limit at the crack source under the surface hardened layer. The effect of shot peening was to shift the source of cracking into the residual tensile stress region beneath the surface hardened layer. They suggested that the fatigue limit in this location was about 1.35 times greater than that of a non peened specimen. In the present work the effect of shot peening the powder metallurgical steel was to increase its fatigue limit stress by a somewhat smaller factor of 1.1. This difference may be the consequence of the different test procedures used. Wang et.al. employed three point bend tests whereas push-pull testing was used in the present work where the loading stress gradient was lower, as mentioned earlier.

4. Conclusions

a) Shot peening smooth air cooled forged steel specimens was found to have little effect (C70S6, -2%; 1141V, +2.5%) on their fatigue limit strengths. In the case of the powder forged steel, a marginal 10.3% increase was observed, albeit with a larger standard deviation.

b) For these smooth push-pull specimens, it is suggested that since shot peening produces a gradient of residual compressive stresses greater than that of the loading stresses, no significant improvement in fatigue accrues, as observed.

c) It is suggested that the work hardening caused by shot peening is more beneficial in improving the fatigue strength than the accompanying induced residual compressive stresses which can relax during cycling.

5. Acknowledgments

Financial support was supplied by the Natural Sciences and Research Council of Canada. The author is most grateful to Dr. Guangxu Cheng, Xi’an Jiatong University, Shaanxi, China for his diligent and careful work in carrying out the fatigue tests. Also, the author wishes to thank Marlene Dolson for typing the manuscript.

6. References

[1] J.E.Hoffman, D.Lohe, E.Macherauch, Influence of shot peening on the bending fatigue behaviour of notched specimens of Ck 45, in V.Wohlfahrt, H.Kepp, O.Vohringer (Eds). Proceedings ICSP-3, Garmisch-Partenkirchen, DGM Informationsgesellschaft, Verlag, Oberursel, Germany, 1987, pp. 631-638

[2] H.Guechichi, L.Castex, Fatigue limits prediction of shot peened materials in International Scientific Conferences on Shot Peening, ICSP-9, Paris, International Scientific Committee for Shot Peening, Mishawaka, Indiana, USA, 2005, pp. 221-228.

[3] D.Eifler, D.Lohe, B.Scholtes, Residual Stresses and Fatigue of Metallic Materials, in V.Hauk, H.Hougardy, E.Macherauch (Eds). Residual Stresses, Measurement, Calculation Evaluation, DGM Informationsgesellschaft, Verlag, Oberursel, Germany, 1991, pp. 157-166.

[4] S.Wang, Y.Li, M.Yao, R.Wang, Fatigue limits of shot peened metals, Journal of Materials Processing Technology, 73, Issue: 1-3, (1998), pp. 57-63.