# The role of shot peening in the design of an innovative twin engine pack system (TEPS) for helicopters

A. Gilioli [a], D. Braconi [a], S. Bagherifard [a], H.Y. Miao [b], M. Bandini [c], F. Pozzi [d], R. Papetti [e], M. Guagliano [a]
[a] Politecnico di Milano, Milan, Italy; [b] Ecole Polytechnique de Montreal, Canada; [c] Peenservice Srl, Bologna, Italy
[d] AQM Srl, Provafglio d'Iseo, Italy; [e] Robby Motor Engineering Srl, Casalmaggiore, Italy

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## Introduction

TEPS is a twin-internal combustion engine developed at Robby Motor Engineering in order to motorize a twin-engine helicopter in the category of Very Light Rotorcraft CS-VLR. More in detail, despite coming as a "single unit" (single engine body), the TEPS motor is the rational integration of two engines capable of operating in-sync in a modular manner, but when it is required, also individually and independently. With this architecture, helicopters equipped with the TEPS are allowed to fly over built-up areas in Europe and other countries where strict regulations do not allow light helicopters with a single engine to fly over such areas. With respect of twin-turbine helicopters, TEPS allows to strongly reducing the operative costs and, at the same time, by including the two engines in a single body, reduces the final total weight of the vehicle, allowing an increase of the pay-load. This makes the TEPS a very attractive solution even for new possible applications. Among these latter, pilot training and territorial and environmental monitoring, can be considered the most immediate ones. Another advantage of TEPS is the ability to use automotive gasoline instead of Avio gas, making easier the refilling. Inside the Pack unit, the two engines are placed in parallel, while the cylinder arrangement is horizontal and opposed. Each engine consists of a group of four cylinders and is equipped with its own lubrication system, power supply and electronic control. Bearing in mind the final application of TEPS, its performances are critical, especially concerning the weight reduction and the reliability. In order to enhance the performances, it is necessary to pay a great attention at the design of the system and of its components, by adopting all the possible techniques to improve the mechanical properties of the machine elements. In this paper, the attention is focused on the crankshaft, made with the low-alloy steel 39NiCrMo3, the most critical part with respect of fatigue design due to its complex geometry and the multiaxial stress state. The design of the crankshaft has been carried out by finite element simulations; for the improvement of the fatigue behavior, the effect of shot peening, nitriding and their combination has been investigated. Particular attention has been devoted to the design of a specimen able to replicate, as close as possible, the stress state in the most stressed geometrical detail of the crankshaft, in order to get results that can be directly used for the fatigue strength assessment of the crankshaft under the expected loads.

## Objectives

The main objective of this paper is to draw an integrated FEM/Experimental procedure for the fatigue design of the crankshaft of the TEPS engine taking into account the effect of shot peening, nitriding or a combination of both these treatments. The methodology has been applied since the design stage of the product, and it is aimed at correctly addressing the choice of the optimal treatment parameters. Even if the procedure is focused on the TEPS system, it can be easily generalized and the present paper can be rather considered a significant application of a general procedure over a real industrial product.

## Methodology

The fatigue design procedure starts from the analysis of the finite element model of the crankshaft developed in [1]. From the FE model, it is possible to identify the most stressed area in terms of maximum Sines stress (the parameter that has been used for the fatigue strength assessment as described in [2] and [3]). The most stressed area, in terms of Sines stress, is close to the round of the connecting rod journal as shown in Figure 1. The second step is to define the experimental coupon shape in such a way it is possible to reproduce the same stress gradient as in the real component and finally perform the fatigue test. Fatigue tests have been performed for the following treatment combination:

- Quenched and tempered
- Quenched and tempered, shot peened
- Quenched and tempered, nitrided
- Quenched and tempered, nitrided, shot peened
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The fatigue strength (run-out=5.000.000 cycles) for each treatment is determined by means of a stair case method [4] and the results discussed in the following.

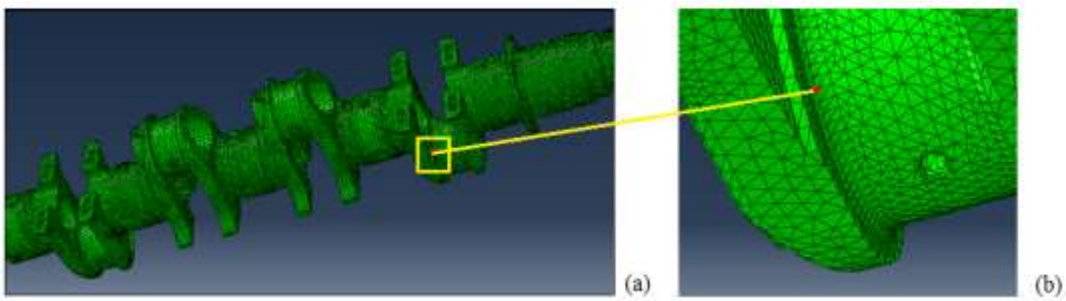


Figure 1 FE model of the crankshaft a) overall view b) zoom on the location where the Sines stress is the highest

**Results and analysis**
***Literature review***
Among the possibilities to improve the fatigue performances of a steel, two surface treatments are the most attractive: shot peening and nitriding. During shot peening, spherical shots are thrown against the target inducing a compressive stress state, which prevents crack initiation and retard crack propagation. Whilst shot peening is a mechanical treatment, nitriding is a thermo-chemical process. It diffuses nitrogen into the surface of a metal to create a hardened surface and to improve fatigue properties. The solid solution of nitrogen in the metal substrate and the nitride precipitates are responsible for hardness increase and for compressive residual stresses in the diffusion layer. Without testing evaluations is almost impossible to determine if the fatigue life increment is higher thanks to shot peening or nitriding and it is not even straightforward the evaluation of the mixed effect due to the combination of the two treatments. Indeed, some studies suggest to perform shot peening before nitriding and some works focuses on the shot peening application after nitriding. Shot peening followed by nitriding treatment have been investigated in [5], where the authors highlighted that performing shot peening before nitriding allows to reduce the needed temperature for nitriding and therefore it is possible to use this heat treatment also for steels more sensible to high temperature. In [6] the authors demonstrate that if shot peening is performed before nitriding, not only the maximum needed temperature decreases but also the hardened surface increases its thickness and its hardness as well. Shot peening followed by nitriding increases the nitrogen rate by reducing grain size and increasing the grain boundary. The second process nitriding followed by shot peening increases the fatigue properties of the component by inducing the compressive residual stress in the component. Several researchers have also studied the effect of shot peening

after nitriding. In [7] and [8] the effect of severe shot peening in combination with nitriding on the microstructure and on the fatigue strength of smooth specimens of a low-alloy steel is investigated finding a positive action of severe shot peening in reducing the nitriding time without affecting the fatigue strength. In [9] the authors show an increment of around 20% performing shot peening after nitriding rather than only nitriding. In [10] the estimated increment is around 5-10%. In [11], the fatigue limit is increased of only 3% for smooth specimen but the increment is of 21% for the notched one. Finally, in [12], the bending fatigue limit is of 8% for only nitriding specimen and it is of 35% for the combined nitriding plus shot peening. From the literature review, it appears that the shot peening performed before nitriding creates better conditions for subsequent nitriding even if the increment of the fatigue limit is not so remarkable. On the contrary, if shot peening is the last treatment, this leads to the highest fatigue strength increment; this is the case considered in this paper. However, while, in general, it is expected that the fatigue limit will increase using both treatments, their effect depends on the type of component and on the stress state and it is not possible to anticipate the quantitative results of them or of their combination. Therefore only after an experimental program on a specimen where the stress state and the in-depth stress gradient is similar to the real one will be possible to draw final conclusions and to choose the final treatment.

***Design of the specimen for the fatigue test***

The design of the fatigue test and, in particular, of the fatigue test specimen has been done starting from the FE analysis of the crankshaft. The starting point regards the correct evaluation of the stress state of the crankshaft. In order to do that it is necessary to exploit the FE model of the system described in detail in [1]. The FE model is built using the real geometry of the crankshaft and meshed by means of solid elements. The complete fatigue cycle of the crankshaft has been simulated with static analyses and by considering the different directions of the applied loads (due to the gas combustion and to the inertia) with respect of the crankshaft axis during a complete four-stroke engine cycle (720°, two full rotations simulated with a step of 5°). For each analysis, the loads are provided by a multibody model of the shaft, developed in [13]. In Figure 2, is shown the Von Mises stress map corresponding at the angular position when the applied loads are the highest. For what concerns the fatigue analysis, a dedicated subroutine has been built in Matlab. The code automatically run the sequence of static analysis describing a working cycle, adopting the correct load for the angular position under exam, up to the post processing of the results and hence the plot of the Sines stress on the crankshaft.

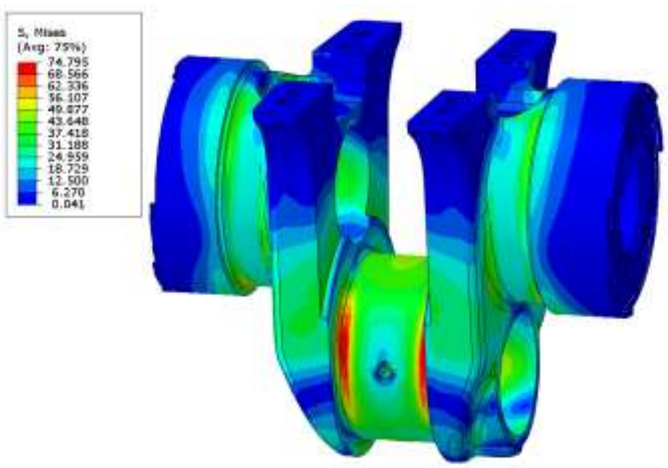


Figure 2 Von Mises stress distribution in the crankshaft at the angular position when the load is the highest

The experimental fatigue tests are performed considering an alternate axial load with a stress ratio R=-1. It is thus necessary to define a proper geometry of the specimen in such a way it is possible to replicate a stress state similar as much as possible at what happens in the real component (crankshaft). From the FE model developed in [1], it is possible to determine the value of the Sines stress for every point of the components. The maximum values of Sines stress, which equals to 177MPa, is located on the round of the connecting rod journal as shown in Figure 1 and in agreement with Figure 2. In order to determine the geometry of a specimen able to correctly reproduce the most stressed detail of the crankshaft, it has been necessary to design a notched specimen able to reproduce the same in-depth stress gradient in that zone of the crankshaft. Therefore, the stress gradient in a direction normal to the surface of the most stressed geometrical detail of the crankshaft has been measured. The general geometry of the adopted specimen is shown in Figure 3: it represents a round specimen with a semi-circular notch with assigned radius, while the test considers an axial load. To get the right stress gradient different values of the notch radius R were considered and FE simulations performed. Due to the symmetry of the problem, it was possible to simplify the model by using axisymmetric elements and modeling only quarter of the real coupon, Figure 4.

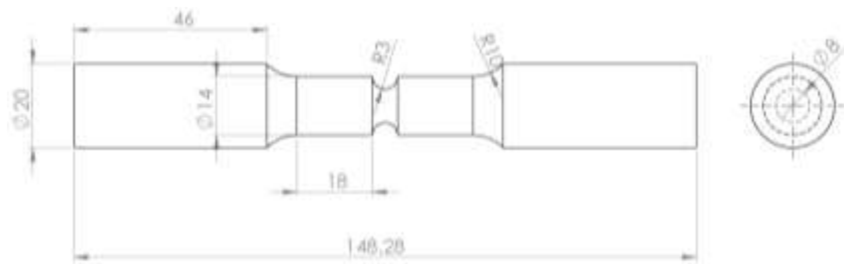


Figure 3 Specimen for fatigue test

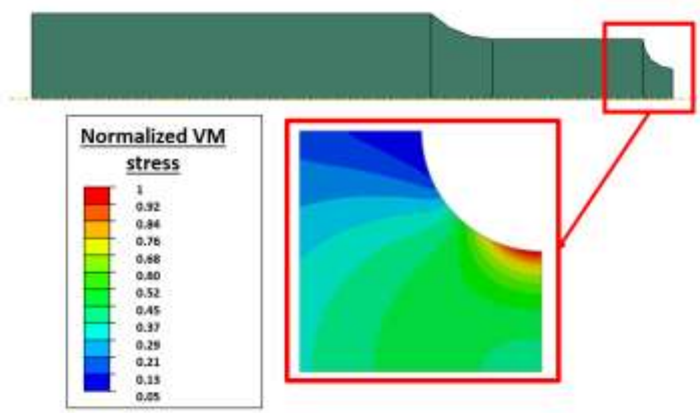


Figure 4 numerical model of the specimen adopted for the tensile test (top), contours of the normalized Von Mises stresses (divided by the maximum stress) close to the round (bottom)

In Figure 5, the FE results in terms of in-depth non-dimensional stress trend, in specimens with different notch radius R, are reported. It is noted that R=3mm is the radius that gives a stress tend quite close to the one of the crankshaft up to 0.6mm from the surface, thus larger than the zone where the fatigue damage and fatigue crack initiation takes place. The size of the drawing of the specimen adopted for the fatigue test is reported in Figure 3, where it is important to notice the choice of R=3mm as radius of the notch.

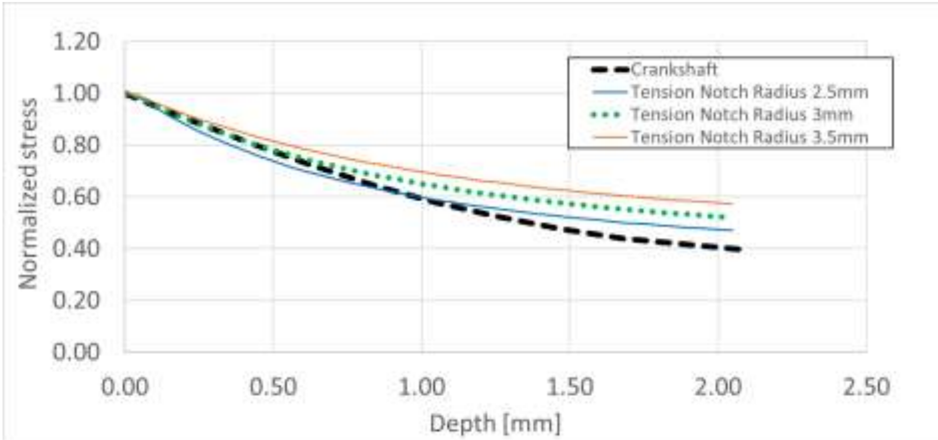


Figure 5 Comparison of the gradient of the radial stress in crankshaft and notch specimens with different notch radii. The normalized stress is obtained dividing by the maximum stress

***Results of the experimental fatigue test***

The experimental fatigue program consists into a high cycle fatigue (HCF) axial test in force control. The applied load is an alternate one with a stress ratio R=-1. The maximum load is 14.5KN and the load step is of 0.7KN. The run-out number of cycles is set as 5E6 cycles and the frequency of the test is 100Hz. The procedure adopted for the determination of the fatigue limit is the staircase method and the results are summarized in Table 1. Concerning the shot peening parameter, a coverage of 100% has been set using S170 shots. For the only quenched and tempered coupon, a required intensity between 10 and 12 A was required getting experimentally the value of 11.1A. Considering the specimen quenched, tempered and nitrided before being shot peening, an intensity between 14 and 16A was required; the measured value was 15.3A.

Table 1 Summary of the experimental fatigue test (Run-out=5.000.000 cycles)

| condition | number of specimen | fatigue strength | standard deviation | standard error | Max ftg strength | Min ftg strength | difference |
|---|---|---|---|---|---|---|---|
| | | MPa | MPa | MPa | MPa | MPa | % |
| Quenced, tempered | 17 | 284.3 | 39.0 | 9.5 | 293.8 | 274.9 | 0.0 |
| Quenced, tempered, shot peened | 17 | 344.5 | 14.7 | 3.6 | 348.0 | 340.9 | 21.2 |
| Quenced, tempered, nitrided | 15 | 351.0 | 20.0 | 5.2 | 356.1 | 345.8 | 23.5 |
| Quenced, tempered, nitrided, shot peened | 16 | 410.6 | 11.4 | 2.8 | 413.4 | 407.7 | 44.4 |

From the experimental tests, it appears that, as expected, the adoption of nitriding or shot peening or a combination of them, leads to an important increment of the fatigue limit of the material, ranging from 21.2% up to 44.4%. This shows the importance of the application of a surface treatment in order to improve significantly the performance of the material. The application of only nitriding, or only shot peening, has more or less the same incremental effect of around 22%. The combination of both technique, applying first the nitriding and then the shot peening, leads to the highest increment of the fatigue strength of around 44% (which is practically the sum of the incremental effect of both treatment).

**Conclusions**

In the present paper the results of an experimental program aimed at the evaluation of the effect of shot peening, nitriding and their combination on the fatigue strength of a low-alloy steel crankshaft of an innovative twin internal combustion engine (TEPS) are reported and critically discussed. The geometry of the specimen has been chosen by means of a finite element model of the crankshaft where the real working loads are applied. In such a way, the tested specimen has a stress state which is very similar to the real one in the area where the fatigue stresses are the highest. The paper demonstrates that both nitriding technique and shot peening allow increasing the fatigue limit of around 22%. The combination of both techniques with shot peening as last treatment increases the fatigue limit of around 44%, which means the cumulated effect of both methods. It is important to remark that each treatment has its peculiar characteristic which are reflected especially in terms of the residual stress profile (nitrided coupons has a thin but with highest compressive stress whilst shot peened specimen has a residual compressive stress up to a deeper point in the material but with a lower stress level). Therefore, the choice of the correct treatment depends highly from the knowledge of the real working condition of the system but it is strongly suggested because it increases the performances of the material greatly at a reasonable cost.

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