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FATIGUE FAILURE OF WATER PUMP SHAFT

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Examination of a broken 3 inch diameter pump shaft showed that premature failure was due to excessive deflection and to cyclic bending stresses.

Corrosion, lack of radius in the keyway, use of the steel in the annealed condition and vibration introduced by the method of coupling and alignment were probable contributory factors.

Changes in shaft strength, surface finish, keyway design and installation were recommended.

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INTRODUCTION

On January 6, 1964, Mr. D. H. Milnes, President, McMullen-Perkins (1962) Limited, Ottawa, submitted a broken pump impeller shaft which had been removed from service at the City of Hull water works. Mr. Milnes requested that the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys carry out a metallurgical examination to determine the cause of failure after approximately one year of total service.

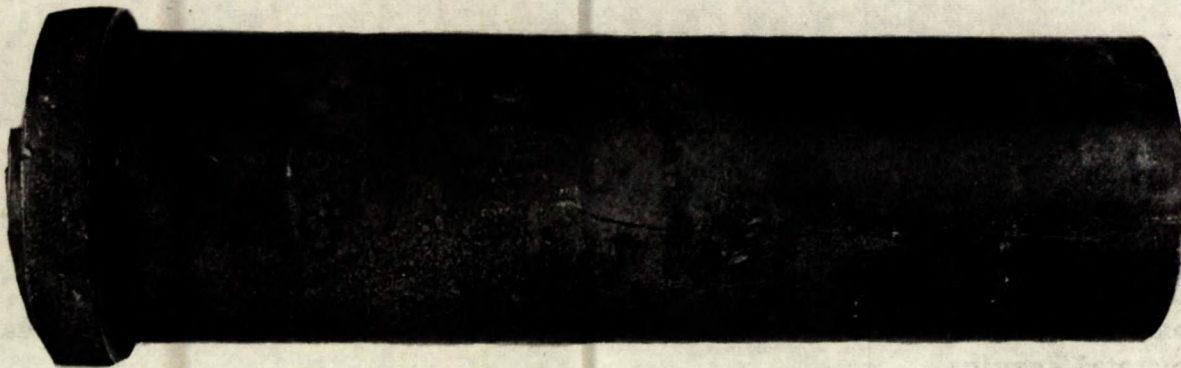
The shaft diameter, after machining, was 3 inches, except in the shoulder region where the diameter was 3-1/4 inches, indicating that approximately 1/4 inch of the bar diameter had been removed by machining.

The shaft was five feet in length and supported a bronze impeller at its midpoint. Bronze sleeves fitted over the shaft at each side and were attached to the impeller. The shaft was driven at one end by a worn coupling and was supported by self-aligning roller bearings at each end of the shaft. The use of self-aligning bearings was a recent change as the original de Laval installation used tin bronze sleeve bearings. The pump is approximately fifty years old and is now in standby service involving periods of shutdown and operation during peak load so that the year of service may have required several years to accumulate.

The original installation was reported to have given little trouble until the latter stages of the fifty year period when changeover of bearings, and, realignment, and balancing were carried out. Despite this, failure of the shaft occurred in a relatively short period. Throughout the pump's service, several replacement shafts have been used. One of these shafts failed by fracture, due to bending stresses, with the fracture located on the side of the impeller remote from the drive end, (i.e., without torsion). Shaft failures appeared to be associated with vibration and with excessive shaft deflection and usually occurred in the same region as observed in this shaft.

Subsequent metallurgical examination showed the failed shaft to have a hardness of only 200 BHN (3000 kg load) and a microstructure consisting of lamellar pearlite and ferrite. Examination also showed that the fillet and keyway were not adequately radiused. Corrosion pits on the shoulder and considerable rust on the keyway suggested that chlorinated water had access to the shaft.

The appearance of part of the broken shaft, extending from the fracture for about 12 inches toward the drive end, is shown in Figure 1.



X1/2

Figure 1. Broken Pump Shaft. Fracture at Extreme Left of Picture.

Figure 2 illustrates the fracture surface with a fatigue crack starting at the rusted keyway and progressing in two directions to meet at the point where final rupture occurred, (position indicated by the arrow).



X1

Figure 2. Appearance of Fractured Pump Shaft. Fracture appeared to start at the keyway and to propagate to the region of final rupture marked by the arrow. The applied stresses were light in relation to the shaft sections.

METHOD OF EXAMINATION

Metallurgical examination was carried out as follows:-

- (i) Chemical analysis of drillings.
- (ii) Hardness test, deep etch and sulphur print of transverse section.
- (iii) Metallographic examination.

RESULTS OF EXAMINATION

(i) Chemical Analysis

The results of chemical analysis are shown in Table 1.

TABLE 1

Results of Chemical Analysis (Per Cent)

Sample	C	Mn	Si	S	P	Ni	Cr	Mo
Pump Shaft	0.40	0.58	0.29	0.031	0.018	1.38	0.83	0.36
AISI 4340	0.38/ 0.43	0.60/ 0.80	0.20/ 0.35	0.040 max	0.040 max	1.65/ 2.00	0.70/ 0.90	0.20/ 0.30

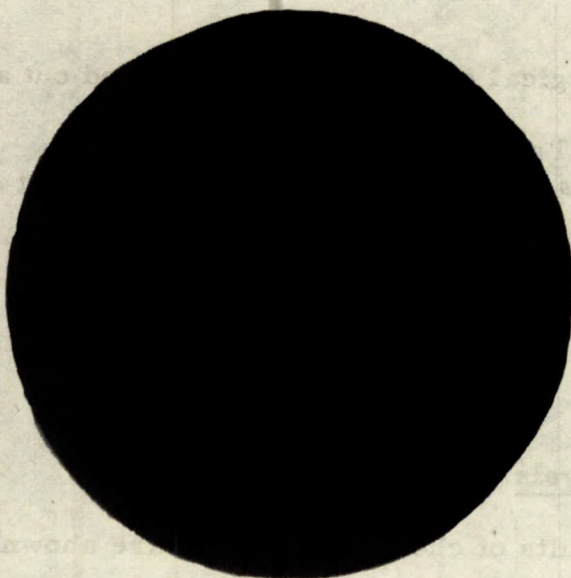
The composition of the shaft conforms to the chemical requirements of AISI-Type 4340 except that the nickel content of this British manufactured steel is slightly lower than the AISI grade.

(ii) Hardness Test and Deep Etch

Brinell hardness results of 187 to 201 (3000 kg load) and Rockwell B hardness results of Rockwell B 90 to 92 were obtained on a ground cross-section through the shaft.

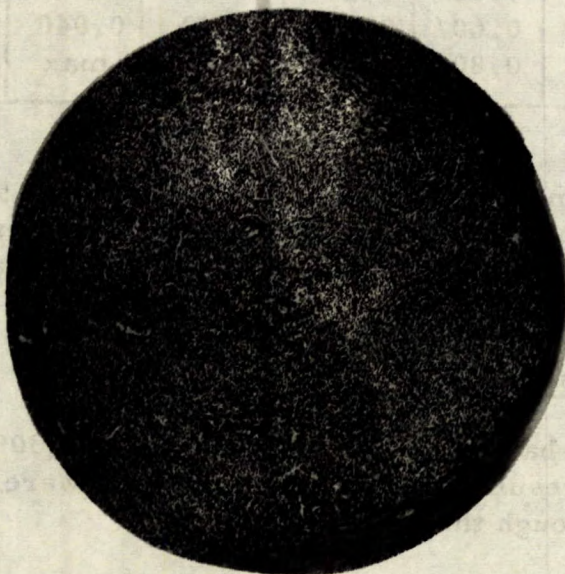
The appearance of a deep-etched section through the bar is shown in Figure 3.

Figure 4 illustrates the appearance of a sulphur print made on the transverse section.



X1

Figure 3. Deep-Etched Cross-Section Through Shaft.
Etched for 20 minutes in 1:1 HCl:water at 71 - 82 °C (160 - 180 °F). The bar quality appears to be excellent with respect to cleanness and freedom from segregation.

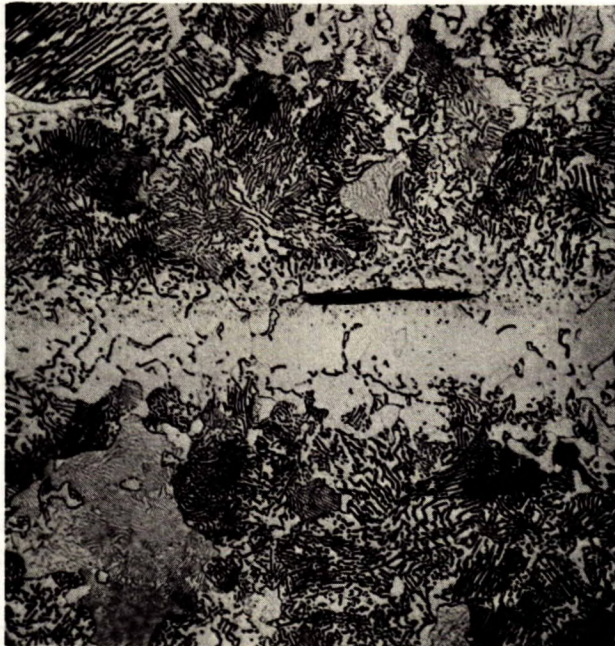


X1

Figure 4. Sulphur Print of Ground Transverse Section Through the Shaft.
This test revealed no unusual quantity or distribution of non-metallic inclusions in this bar.

(iii) Metallographic Examination

The appearance of a photomicrograph taken on a transverse section through the broken shaft is shown in Figure 5. The microstructure consists of ferrite and lamellar pearlite and contains pearlite-ferrite bands due to slow cooling.



X500. Etched in 2% Nital.

Figure 5. Transverse Section Through Broken Shaft.

The microstructure and hardness (BHN approximately 200) show that this shaft was used in the annealed condition.

SUMMARY AND DISCUSSION

The chemical composition and quality of the bar used for the shaft appear to be satisfactory; however, use of this steel in the annealed condition at 200 BHN provided a low yield strength of approximately 75,000 psi, whereas in the oil quenched and tempered 538°C (1000°F), condition at 340 BHN a corresponding yield strength of 125,000 to 150,000 psi would have been obtained. Information since receipt of the original

shaft and pertaining to a second shaft cut from the same length of bar confirms that excessive deflection did occur in this second shaft so that it failed by deformation (bending) but without fracture. The keyway in this second shaft was correctly radiused and, unlike the shaft discussed in this report, did not provide an origin for crack development and fatigue failure.

CONCLUSIONS

1. The steel composition and quality were suitable but the bar should have received an oil quenching and tempering heat treatment to approximately Brinell 340.
2. The shoulder fillet and the keyway appeared to lack adequate radii.
3. Severe rusting of the keyway surface and pitting of the shoulder indicate access of water to the steel surface. This would be expected to reduce the endurance limit of the steel.
4. Fracture was due to fatigue failure caused by excessive deflection and reverse bending stresses acting on annealed steel in the presence of moisture. Fracture appeared to start at a poorly radiused keyway and to progress under the repeated application of cyclic stresses. The magnitude of the applied stress appeared to have been relatively light since the cracks propagated without failure until final rupture on the small area marked in Figure 2.
5. Variables, such as motor alignment, insulation, access of moisture to the shaft, dynamic balancing and coupling wear, required investigation to determine if shaft deflection can be reduced.
6. Traces of copper were detected by X-ray fluorescence examination of rust taken from the keyway surface.

RECOMMENDATIONS

1. Replacement shafting should contain sufficient alloying elements to allow through-hardening in the 3 inch section by quenching and tempering. For example, the steel used in the present shaft, or steel conforming to the chemical requirements of AISI-4340, could be used at 340 BHN hardness corresponding to a yield strength of 150,000 and to an endurance limit of approximately 80,000 psi in reversed bending.
2. The keyway and shoulder should be properly filleted; the shaft should be polished and should be protected from water during service. (Reduction of the endurance limit to less than 30% of normal value has been reported for steel in water, stressed in reversed bending.)
3. Mechanical aspects, pertaining to alignment, coupling, bearings, and balancing should be investigated.
4. The possibility of any galvanic action between bronze and steel in water should be avoided during shutdown and operation of the pump.

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