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EXAMINATION OF THREE ROCK DRILL PISTONS FOR USE IN THE INGERSOLL-RAND JR 300A ROCK DRILL (T.I.S. 58,733)

by

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PHYSICAL METALLURGY DIVISION

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EXAMINATION OF THREE ROCK DRILL PISTONS FOR USE IN THE INGERSOLL-RAND JR 300A ROCK DRILL (T.I.S. 58,733)

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SUMMARY OF RESULTS

Metallurgical examination of three failed 1% carbon steel rock drill pistons showed that two of the failures were due to severe deformation of the striker end, followed by formation of transverse fatigue cracks and spalling of the splines adjacent to the striking face.

Failure of the other piston appeared to be unusual, having occurred at the midpoint of the striker shaft. The origin of the fatigue fracture in this sample appeared to coincide with a steel defect.

The chemical composition was as specified in all samples - in one sample the double austenitize heat treatment left the hardness transition zone in close proximity to a spline fillet.

It was observed that the hardness pattern did not follow the contour of this component as uniformly as with induction hardened components.

The surface hardnesses of R_c 59 to 61 and the core hardnesses of R_c 38 to 40 appeared to provide a wear resistant surface combined with a relatively soft and tough core.

The main transverse cracks appeared to progress from the outside surface rather than the bore surface.

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INTRODUCTION

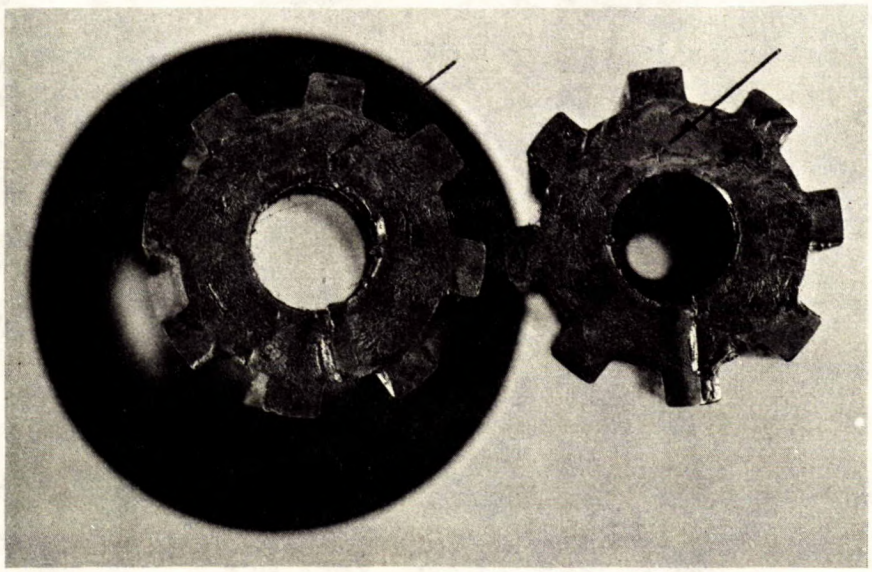
Two rock drill pistons and an etched section from a third piston, illustrating premature service failures of this component in Ingersoll-Rand, JR 300 Rock Drills, were submitted to the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys with the request that, if possible, the cause of premature failure be determined by metallurgical examination, (ref: T.I.S. File No. 58733, October 16, 1964/E.N. King. Letter from Mr. D.S. McCann, General Manager, J.M.G. Manufacturing Limited, November 3, 1964).

The pistons were identified as No. 1, 2 and 3 for the purpose of this report.

Piston No. 1 appeared to have been in service for a considerable time prior to failure, so that measurable wear had occurred on the large diameter. Failure occurred by battering of the drive-end surface of the piston. The appearance of this end of piston No. 1 is illustrated in Figure 1.

Figure 1. Piston No. 1 view of battered drive end of piston. Piston impacts 750 times/minute; revolves 25 times/min. Premature failure occurs in one out of 20. Location of a transverse crack is marked (arrow).

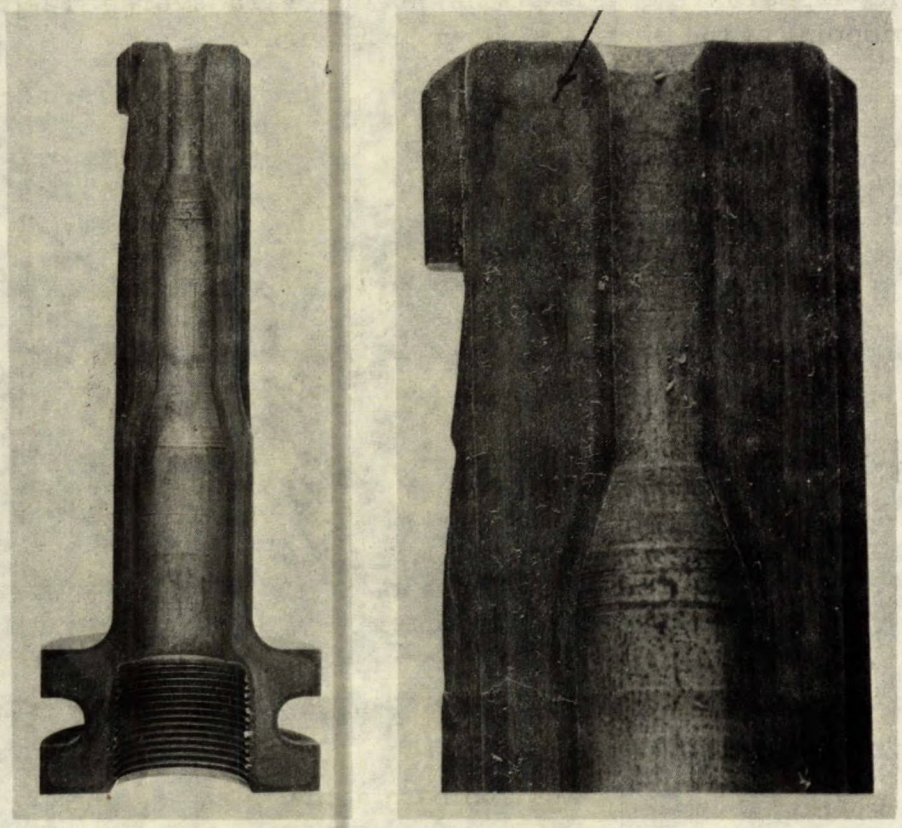
Piston No. 2 appeared to have been in service for only a brief period when failure occurred by transverse fracture at the midpoint of the shaft (region corresponding to maximum bending). This fracture appeared to have an origin in a steel defect. The defect is visible on the fracture surface (Figures 2, 4) and in other transverse sections (Figure 13). Fracture of this piston shaft progressed from the outside inwards, as shown by the presence of bronze on the fracture surface. The appearance of this piston, having a transverse fracture at the midpoint of the shaft, is shown in Figure 2.



approximate actual size

Figure 2. Piston No. 2. View of transverse fracture at midpoint of piston shaft. The apparent origin of the fatigue fracture and the intersection with a steel defect (see also Figures 4 and 13) are marked (arrows).

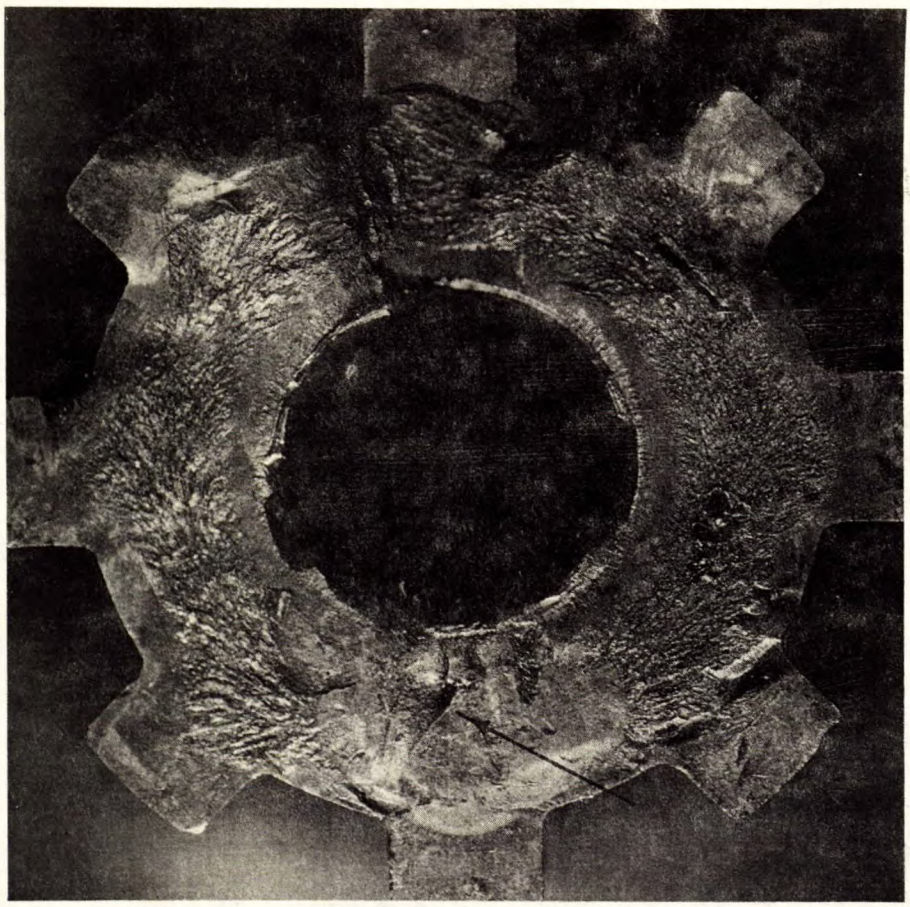
The third sample was supplied as a longitudinal half section, but had been surface ground and deep-etched prior to receipt. This unit, like that shown in Figure 1, had failed by battering of the work surface and by development of a transverse crack adjacent to the compression (driving) end, (arrow Figure 3).



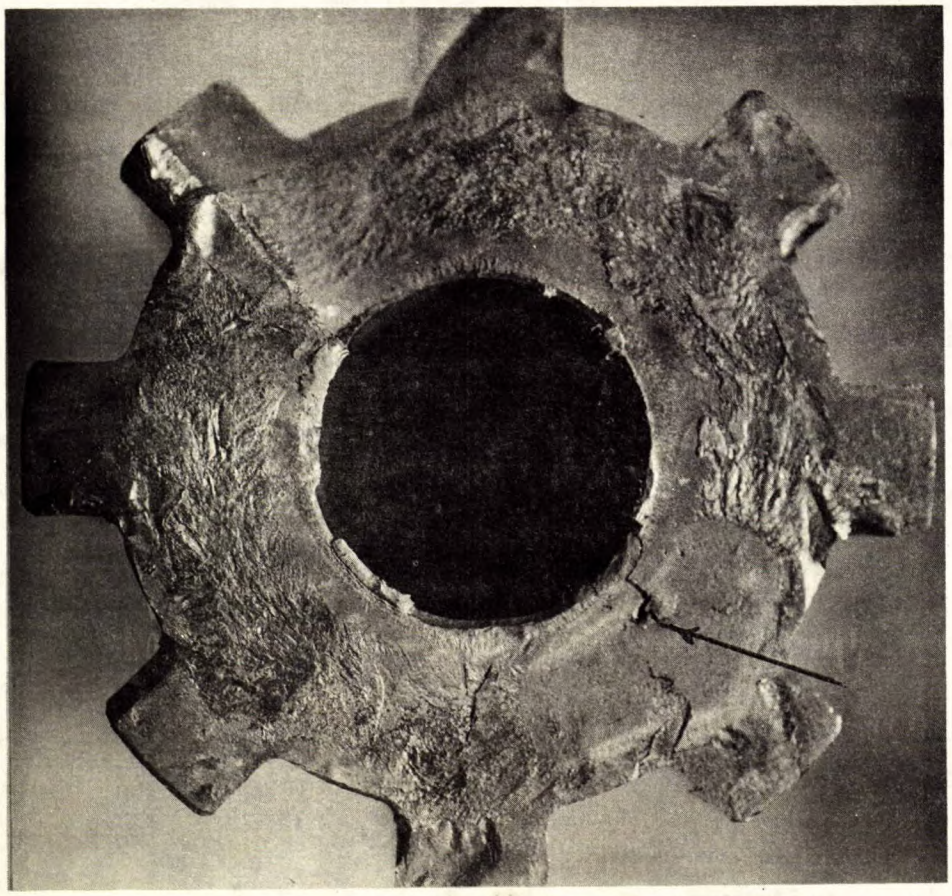
X1/2 X1-1/2

Figure 3. Piston No. 3, half section as-received - etched. This piston, like piston No. 1, had failed by battering of the end, spalling of the splines and by development of a transverse crack (arrow) 1/4 in. from the impact (compression end).

The core metal has a hardness of R_c 38; the surface-hardened metal is visible as a dark line following the external and bore contours. The surface hardness is R_c 59 to 61. Transition from R_c 59/61 to R_c 38 occurs within the darkened etch-zone.

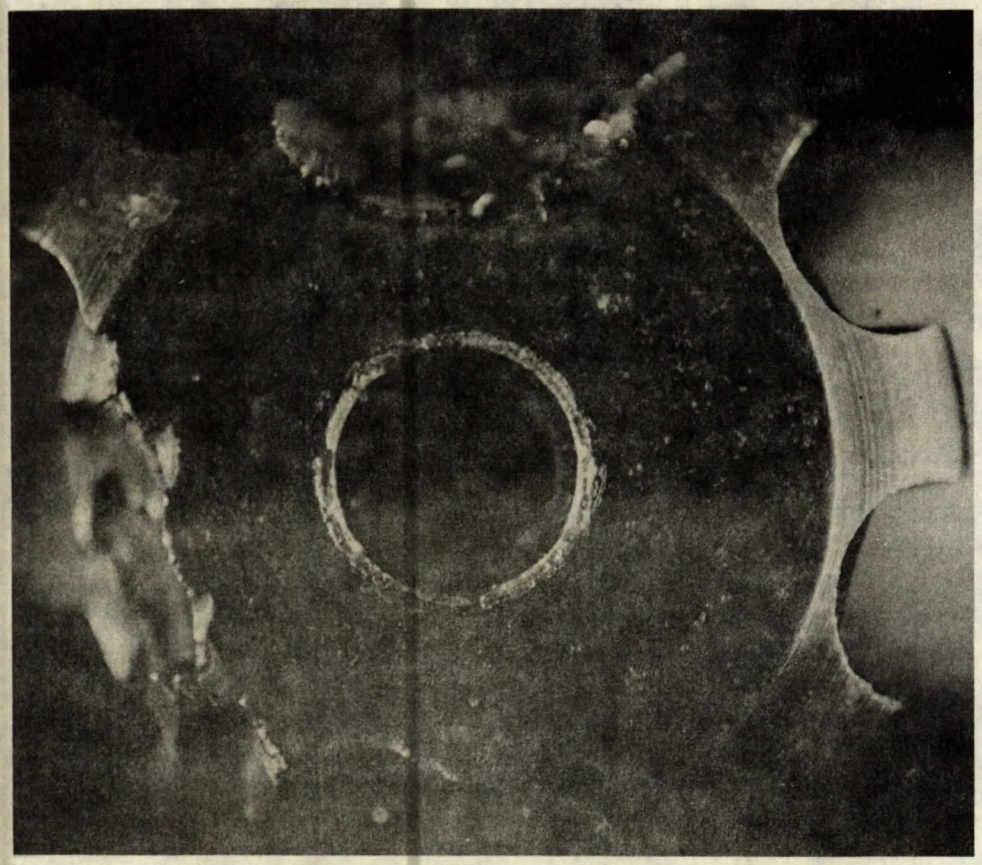


(a) fracture surface - piston shaft - pressure end. X3



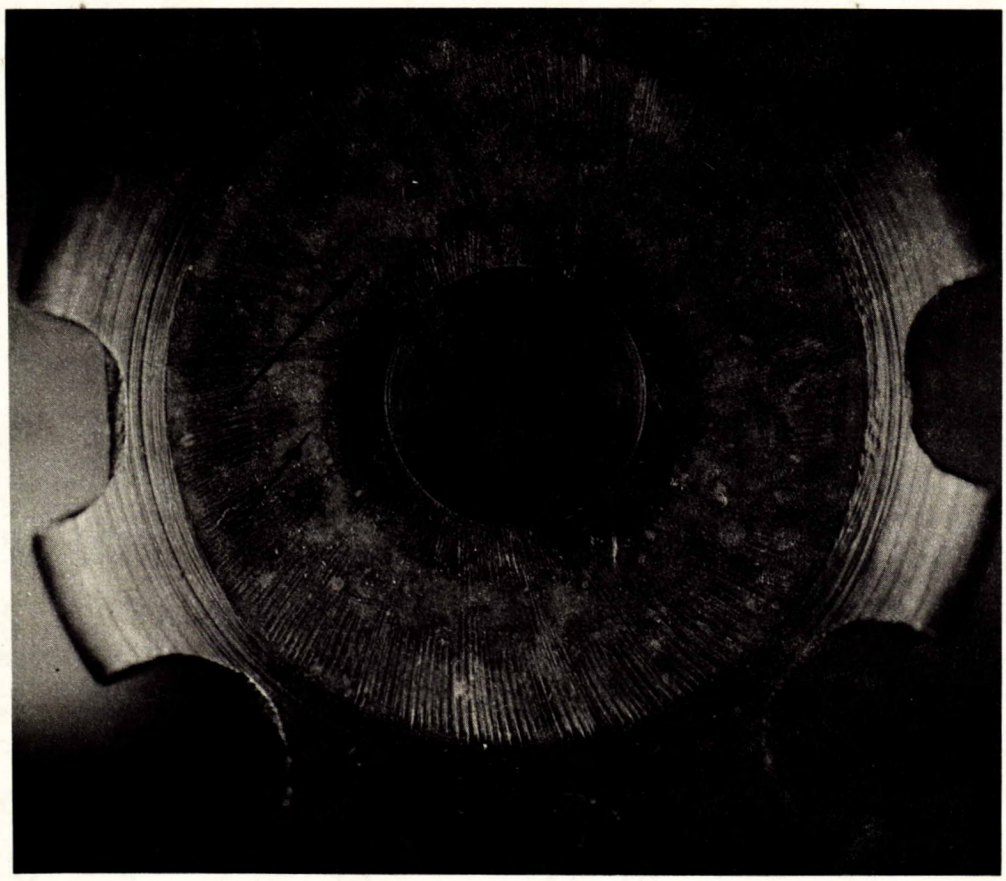
(b) fracture surface - piston shaft - drive end. X3

Figure 4. Fracture, Sample 2, break after short service at mid-point of shaft. The origin of premature fatigue failure is marked by the arrows. This specimen failed in bending fatigue at the mid-point of the shaft.



Actual OD drive end = 1-1/8 in. X3-1/2

Figure 5. Sample 1 (chipped and battered drive end).(Longer life than sample 2). Work face = 1-1/8 in. diameter. This piston appears to have been in service for a considerably longer period than sample 2. The battered work face, chipped splines and subsurface transverse crack is judged to be a typical piston failure exhibiting deformation despite a surface hardness of R_C 60. Sample 3 resembled this piston. The contact surface, 1-1/8 in. diameter, is larger than that of sample 2, 1 in. diameter. The extent of deformation is also illustrated in Figure 11.



Actual OD drive end = 1 in. X3-1/2

Figure 6. Sample 2 (drive end). Workface = 1 in. diameter. (Short life) The work face of this piston shows distinctive markings. If these marks were produced in service, the appearance of ridges in this piston, at R_c61, suggests that the driven steel was harder than the piston — and that there was some roughness or misalignment of the contacting faces.

METALLURGICAL EXAMINATION

Chemical Analysis

The results of chemical analyses made on this steel, after annealing, are listed in Table 1.

TABLE 1

Results of Chemical Analyses (Per Cent)

Sample No.	C	Mn	Si	S	P	V	Cr	Ni	Cu	Al
JMR Piston 1	1.09	0.20	0.18	0.020	0.002	0.18	0.07	0.08	0.08	0.07
" " 2	1.04	0.18	0.13	0.019	0.004	0.18	0.07	0.08	0.07	0.06
" " 3	1.05	0.18	0.15	0.019	0.002	0.19	0.07	0.05	0.06	0.06
*Atlas Special Alloy 10	1.05	0.20	0.20	"	"	0.20	-	-	-	

* Typical analysis for Atlas Special Alloy 10.

The chemical composition of the three pistons is very similar and resembles the typical composition of Atlas Special Alloy 10. (1% carbon tool steel).

Etched Sections

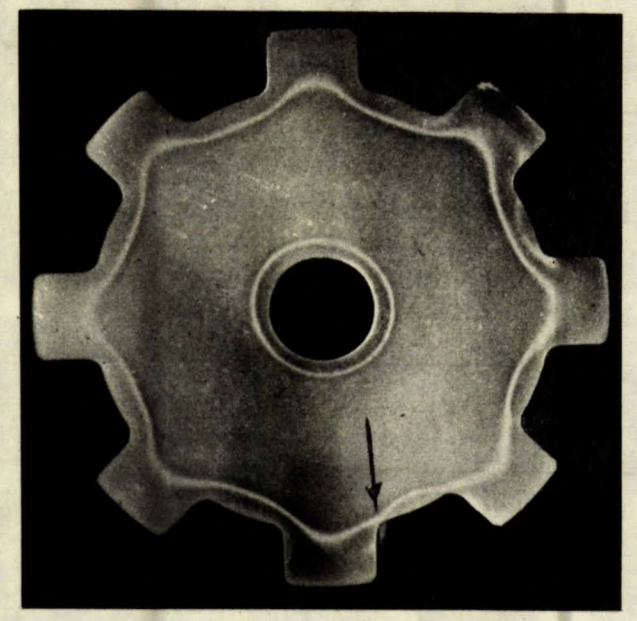
In addition to the deep-etched half section submitted (sample 3), two transverse sections were taken, 1-1/2 in. from the drive ends to compare the depth of the hardening pattern in samples 1 and 2. These sections are illustrated in Figures 7 and 8, respectively. JMR heat treatments are shown in Table 2.

TABLE 2

JMR Production Heat Treatment

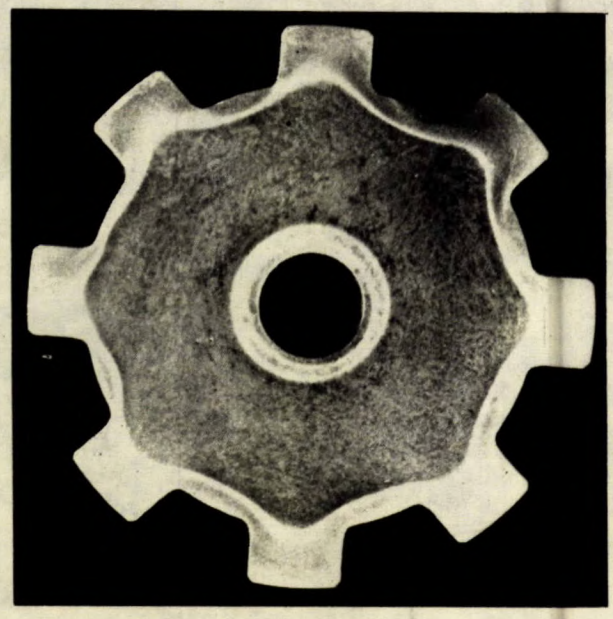
(1) Cyclic anneal (spheroidize)	Neutral salt at 1440°F for 1 hr; cut furnace to 1300°F and hold for 5 hr. Cool in mica.
(2) Austenitize and Quench (Core)	Heat in neutral salt at 1650°F for 1 hr and quench in oil.
(3) Harden surface.	Reheat in neutral salt at 1410°F for 15 min and quench in caustic soda.
(4) Stress relief	Draw at 370°F for 1 hr and air cool.

Figure 7. Sample 1. Transverse section 1-1/2 in. from drive end. The white line indicates the transition zone having a hardness gradient of 55 to 45. The surface hardness is R_c 60/61. The metallurgical notch coincides with the spline fillet in the location marked by the arrow.



Etched potassium iodide and iodine.
X1-1/2

Figure 8. Sample 2. Transverse section 1-1/2 in. from drive end. Note that the hardened bore-hole pattern is considerably thicker in this sample than in sample 1. The hardness pattern does not follow the surface contour, i.e., the case is deep at the splines but is shallow at the grooves



Etched potassium iodide and iodine.
X1-1/2

TABLE 3

Hardness Survey on Transverse Sections
(Figures 7 and 8)

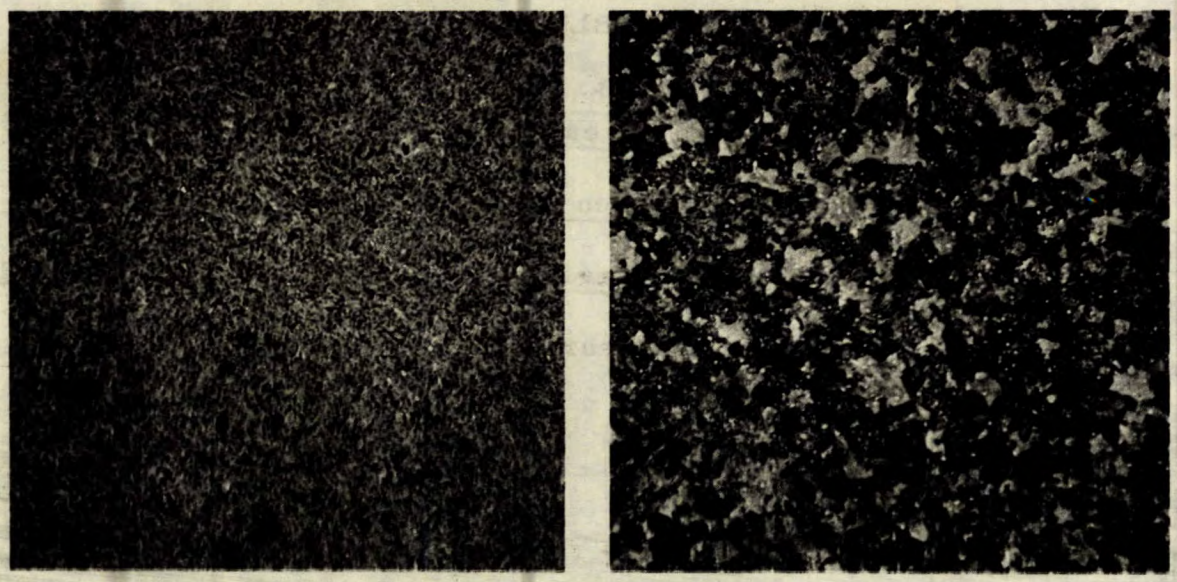
500 g Load Tukon Hardness Test

Sample No.	Distance from Surface	Knoop Hardness	*Rockwell C Hardness
1	0.040 in. from surface	700	59
		700	59
		700	59
		700	59
1	core	376	38
		376	38
		376	38
		376	38
2	0.040 in. from surface	700	59
		**848	65
		700	59
		**769	62
2	core	394	40
		394	40
		394	40
		394	40

* Rockwell C obtained from conversion of Knoop (500 g) hardness
** Note erratic hardness gradient adjacent to the surface of sample 2. The surface hardness was R_C 61.

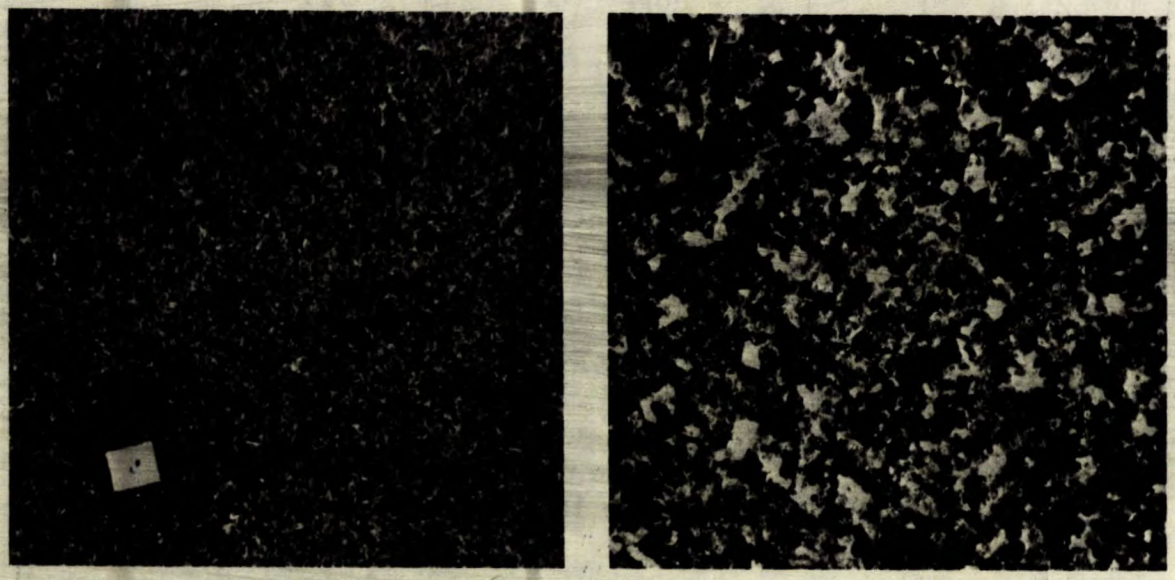
METALLOGRAPHIC EXAMINATION

Figure 9 illustrates the microstructure observed in the case and core of sample 1. Figure 10 illustrates similar areas for sample 2.



(R_c 59) case 2% Nital etch - X500 core (R_c 38)

Figure 9. Sample 1 - Transverse section. The case consists of tempered martensite with traces of undissolved carbide. The core consists of unresolved transformation product. Fine grains and excess carbide.



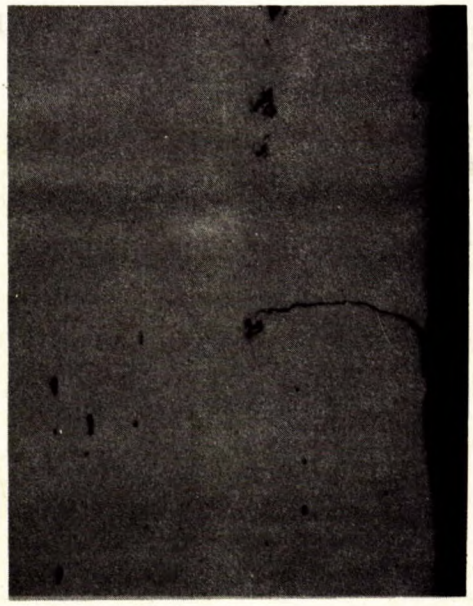
2% Nital etch - X500

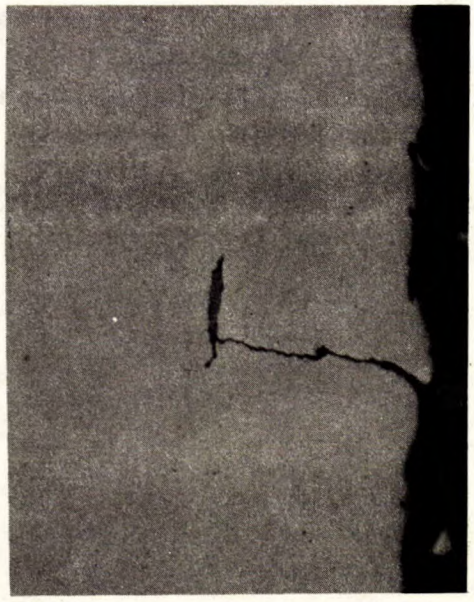
(R_c 59-65) case core (R_c 40)

Figure 10. Sample 2. - Transverse section. The structure is similar to that of Figure 9. The cubical particle shown in Figure 10 (left) appears to be a titanium nitride inclusion resulting from steel mill practice.

As-polished X500

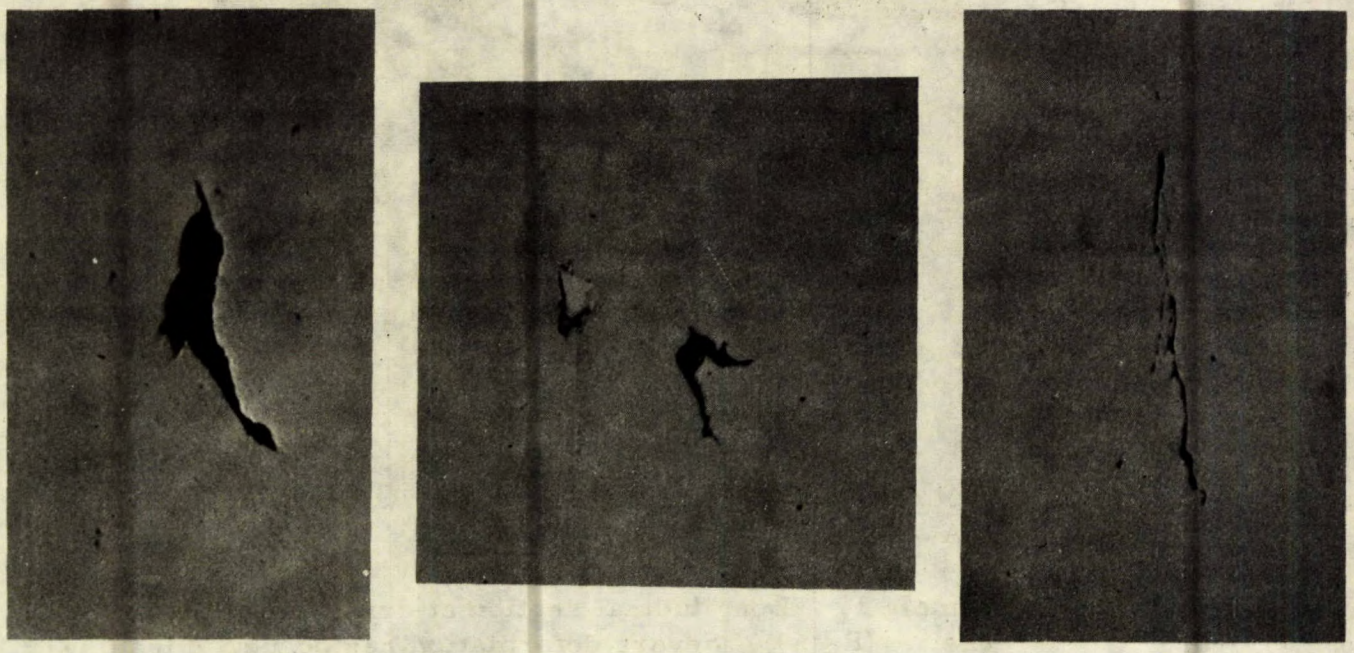
Figure 11. Sample 1. - Longitudinal section at drive end of piston shaft. (R_C 59). Severe deformation has occurred leading to the development of compression cracks and brinelling of the surface. This surface was deformed by compressive stresses in excess of the yield point.





As-polished X500

Figure 12. Sample 1. - Longitudinal section showing fatigue cracks at the inside (hole) surface. The appearance of the cracks suggests that these are fatigue cracks and that they required time to develop. The tips of both cracks are associated with inclusions. The main crack appeared to progress from the outer surface (opposite to this surface).



(a) (b) (c)

As-polished X500

Figure 13. Sample 2. - Transverse sections showing intersection with a longitudinal defect which was aligned with the origin of the fracture. This defect resembled a lap or pipe and extended the full length of the piston shaft. (Figures (a), (b) and (c) illustrate three transverse sections through the defect; (a) was taken approximately 1/2 in. from the fracture origin).

SUMMARY OF OBSERVATIONS

1. Examination of the fractures indicated that samples 1 and 3 had failed due to repeated application of impact forces at the drive end producing stress in excess of the yield strength of the material at a hardness of R_c 59. This type of fracture was characterized by chipping of the splines, by spalling, deformation and brinelling of the driving surface and, finally, by formation of transverse circumferential fatigue cracks approximately 1/4 in. beneath the end surface. (The cylindrical surfaces were worn to approximately 0.001 in. smaller diameter on sample 1 than on sample 2, indicating longer service life on these pistons than that obtained by sample 2).

2. Examination of the fracture on sample 2 suggested that this piston had failed after brief service. The origin of the fracture appeared to coincide with a longitudinal defect present in the bar stock. The crack surface was coated with bronze, indicating that the crack had progressed from the outside inwards rather than from the bore-hole. The ridge pattern, present on the end surface of the piston shaft, if due to service, suggests that this end, as it rotated, was contacting a rough drill rod or tappet surface. Wear had occurred since the ridges were formed as illustrated in Figure 6.

3. Circumferential machining marks were visible on the bore-hole surface; however, except for shallow cracks (Figure 12), the main cracks appeared to progress from the outside inwards and were adjacent to heavily deformed metal.

4. The surface hardness gradients of samples 1 and 3 were more uniform than those of sample 2, indicating some difficulty in reproducing identical quenching and tempering conditions for all pistons.

5. The microstructure of the case of each sample consisted of slightly tempered martensite and numerous small undissolved carbides. The centre of the section (core) consisted of unresolved bainite or fine pearlite and numerous random, undissolved carbides. All samples appeared to be fine grained (less than ASTM No. 7)

6. The appearance of the end surface of sample 1 showed that metal at the piston drive surface had been deformed for a depth of at least 0.010 in., corresponding to stress in excess of 150,000 psi, for metal having a hardness of R_c 59.

7. Spalling and brinelling had reduced the contact area at the drive end of each piston prior to failure.

8. The steel is relatively shallow-hardening, resulting in the hardness transition zone being relatively close to the roots of the splines. The hardening pattern did not follow the contour of the splines so that the splines were through-hardened, whereas the fillet and groove areas were less deeply hardened.

9. Some difference in the depth of hardening observed at the bore hole is visible in comparing samples 1 and 2 (Figures 7 and 8).

10. The chemical composition of the pistons conformed closely to typical analyses for 1% carbon tool steel containing vanadium. (For example, Atlas Special Alloy 10).

DISCUSSION

Metallurgical examination revealed nothing in the chemical composition or heat treatment of the steel to explain premature failure of samples 1 and 3. Failure of sample 2 may have been accelerated by the presence of a longitudinal discontinuity in the steel. (This pipe discontinuity coincided with the apparent origin of the fracture). However, the fracture at the midpoint of the piston shaft in sample 2 appeared to be unusual and not a typical failure.

The heat treatment of all samples had produced a surface hardness of Rockwell 'C' 59-61 that graded to a midsection core hardness of Rockwell 'C' 38-40. The hardness of the outside surfaces was uniform; however, differences were observed in the hardening pattern of the bore holes. In sample 2 the bore hole surface was hardened to Rockwell 'C' 53, whereas the bore surface of sample 1 was only Rockwell 'C' 40 with the maximum hardness occurring about 1/32 in. beneath the bore hole surface.

It was also observed that the transition zone (white lines, Figures 7 and 8) was close to the fillet between a tooth and spline (arrow Figure 7) in sample 1.

Some important factors affecting the fatigue life of rock drill pistons can be listed as follows:

(1) Material
- cleanness
- hardenability
- grain size
- hardness - correct compromise between wear and toughness.

(2) Design
- energy of impact blow.
- mass of piston vs. mass of drill rod ($M_1V_1=M_2V_2$).
- strength to resist brinelling - toughness to avoid crack initiation.
- piston surfaces should be at least as hard as drill rods.
- metallurgical notch should not coincide with a mechanical notch.
- increase or improve contact area of piston-striker and drill rod or tappet being struck.
- avoid machine marks, i.e., consider whether to polish.
- cold rolling might be used to increase surface compressive stresses (alternatively these can be produced by heat treatment.

(3) Finish
- fatigue life is increased by use of polished surface and adequate fillets.

(4) Residual Stress Pattern -case hardening of the outer surface and use of the bore quench should provide favourable compressive stress. (Cold, spiral rolling can sometimes be used to increase surface compression). Induction hardening might produce more uniform contour hardening and residual stress pattern.

(5) Service Environment and Operating Technique
- fatigue life may be reduced in the presence of mine water.
- piston fatigue failures can be caused by the presence of large upsets (inertia) in forged drill rod at the chuck end.
- alignment of the piston striker and drill rod is important in reduction of bending stresses and in avoiding notching, chipping and spalling of the piston striker surface.
- condition of the bronze sleeve may also be significant.

CONCLUSIONS

1. Samples 1 and 3 contained no material or heat treatment defect and appeared to be truly representative of the 5% of production which fails prematurely.

2. Sample 2 appeared to have had an unusually short service life with evidence of misalignment between the piston striker and the drill steel, resulting in marking of the end of the piston striker surface. A defect in the steel bar appeared to have acted as the origin of the fracture in a region of maximum bending stress. This failure was believed to be a non-typical type of failure.

3. The chemical composition of the steel matched the typical composition listed for Atlas Special Alloy 10 - 1% carbon tool steel containing approximately 0.20% vanadium.

4. The core hardness of the steels was R_c 38-40, the hardness of the outside surfaces was Rc 59-61. The heat treatment had been effective in producing uniform surface hardness; however, some variation was noticed in comparison of the bore-quenched surfaces.

5. The transition zone between the surface hardened and the core metal was close to the spline fillet in one area, (sample 1, Figure 7), i.e., the metallurgical notch was close to a mechanical notch.

6. The bruised ends observed in samples 1 and 3 suggest that the drill steel may have had a heavy upset adjacent to the chuck or that rock conditions were difficult.

7. The marks on the end surface of sample 2 suggest that the drill steel or tappet was harder than R_c 61 and that the piston face and drill steel were not well aligned. (There was sufficient roughness in the hard end of the drill steel or tappet to result in marking of the piston striker face). Alternatively, these marks may have been present since manufacture. Some wear occurred after marking.

RECOMMENDATIONS

(A) Assuming Continued Use of 1% Carbon Tool Steel. (Although the writer would consider this a shock application rather than typical die service).

1. Purchase steel to highest standard of cleanness with respect to inclusion stringers (directionality) or consider use of forged blanks. The finished pistons should receive a magnetic particle inspection to reveal any quench cracks, grinding cracks, undercuts, or unacceptable inclusions prior to service.

2. Attempt to obtain uniform surface hardening so that a steep hardness gradient does not coincide with the spline fillets. (This condition would not occur with contour induction hardening* with a deep hardening steel or with a deep carburized nickel steel).

3. Consider the possibility of buying alloy bar stock in the pre-quenched and tempered (R_C 30) condition or doing this at the plant prior to machining to allow use of a single quench hardening treatment. (This would avoid the necessity of reheating the core of the piston above the Ac_3 temperature as now occurs when the second quench is carried out and would leave the core of the piston in the tempered martensite condition rather than the bainitic condition).

(B) Alternate Materials

1. Failure appears to be a consequence of insufficient toughness, possibly use of 0.60% carbon steel would offer a better compromise between toughness and wear resistance. (Much greater toughness might be obtained by use of a single hardening quench simultaneously hardening the outside and bore surfaces as deeply as possible while leaving the core in the pearlitic (fine) condition). This would eliminate both the spheroidizing heat treatment and the 1650°F first quench.

2. Use of prehardened (R_C 38) AISI 8640 (Atlas SPS 245) material hardened by a single quench (surface and bore) would offer greater depth of surface hardness coupled with a tough core of tempered martensite, providing adequate stress relief can be obtained between the surface hardened zone and the core.

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* Commercial facilities are available in Kitchener, Ontario, if a prototype induction hardened unit should be considered.

3. If it is concluded, that increased toughness is required or that design and service conditions cannot be improved to reduce shock loads in excess of the yield strength - use of deep carburized steel e.g. (Atlas Impact) with a core hardness of R_c 20-30 and a stress relieved case (0.060 in. to 0.080 in. deep) at R_c 60-61 could be tried. (The bore hole should also be carburized).

4. The possibility of use of a case-carburized air hardening steel of the type typified by Atlas Javelin or AHT-28 to provide a case depth of 0.060 in. at R_c 60-61 and a bainitic core at R_c 44, could also be considered. (Some mining drill steel is already used in this condition)

5. In addition to the AISI-8640 type of steel discussed (2) use of a through-hardening, medium carbon steel such as AISI-4360 (Ultimo 6) or of shock resisting tool steel could be considered at an intermediate hardness (R_c 55) with the surface spiral rolled to increase the residual compressive stress.

(C) Stress Analysis

Choice of material and manufacturing process should be compatible and should be governed by machine design requirements, having regard to striker energy, drill rod inertia, contact area of the striker, use of tappets, damping of vibrations, etc.

(D) Stress Relief of Pistons Removed from Service

Removal of pistons from service after a prescribed interval of service for stress relief treatment - heating 1 hr per inch of section at 350-450°F has been reported to double the life of tools which tended to fail by sinking due to heavy compressive loads.

APPENDIX

Data Supplied by JMG Company

Piston operates on a horizontal plane, supported on the large end by the cylinder walls and on the small diameter by a bronze bushing. It strikes the steel on the small end approximately 750 times per minute, revolving 25 times with a force of approximately 120 ft-lb, - 80 lb air pressure on the piston face.

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