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WATERTOWN ARSENAL LABORATORY

MEMORANDUM REPORT

NO. WAL 710/520

Heavy Tank T26E1

Metallurgical Examination of Components Which Failed Under Ballistic Tests

BY

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DATE 28 August 1944

WATERTOWN ARSENAL
WATERTOWN, MASS.

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Final Report on Problem B-4.49

28 August 1944

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ABSTRACT

A trunnion shaft supporting the gun carriage was submitted which shattered during the ballistic tests. It was found that the shaft failed because it possessed extremely low impact strength as a result of improper heat treatment of a steel (SAE 6150) having insufficient hardenability for the section size (3¼") involved. It is recommended that the trunnion shaft be made from a steel having sufficient hardenability for a 3¼" round and that it be heat treated to a hardness of 34 to 38 Rockwell C.

Bolts attaching the turret to the upper race ring were sheared during the ballistic tests. The bolts were made from SAE 4140 steel satisfactorily heat treated to a hardness of 31-33 Rockwell C, and it was concluded that the bolts must be made larger if it is expected that they should withstand the stresses resulting from this type of attack.

Bolts attaching the commander's cupola to the turret were fractured during the ballistic attack. The bolts were made from SAE 3140 steel satisfactorily heat treated to a hardness of 33 Rockwell C. It was concluded that they should be redesigned if they are expected to withstand the stresses resulting from the ballistic attack to which they were subjected.

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1. As requested by letter from the Office, Chief of Ordnance - Detroit dated 7 August 1944 (Wtn 400.112/3162(c) - 00 470.5/Watertown Arsenal (7 August)), a metallurgical examination has been conducted on several components of the T26E1 heavy tank which failed under the ballistic test. The parts submitted were listed as follows:

a. Trunnion Shaft - No. B337185.

b. One-half inch (½") bolts connecting the turret to the upper race ring - No. BAOX1.

c. Three-quarter inch (3/4") bolts connecting commander's cupola to turret - Nos. BAPX1EW and A349490.

2. The results of the ballistic tests which failed the subject parts (Reported in APG Report AR 14352) are summarized as follows:

a. After six (6) impacts on the side walls of the turret with 90 mm. APC M62 projectiles, it was observed that the right trunnion shaft had been shattered.

b. The bolts attaching the turret to the base ring were sheared progressively by these impacts; 2 on the first, 4 on the second, 10 on the third, 9 on the fourth, and 2 on the fifth.

c. The firing of a 75 mm. HE Shell at the commander's cupola caused failure of five of the bolts joining the cupola to the turret.

3. The trunnion shaft exhibited low impact properties as a result of poor heat treatment and the use of a steel of insufficient hardenability. The use of a steel of sufficient hardenability (one that can be quenched to martensite in a 3½" round with the quenching medium used) properly heat treated to a hardness of 330 to 360 Brinell would eliminate the shattering type of failure encountered. Severe tests might deform the trunnion shafts, but a brittle fracture probably would not be encountered.

The one-half inch (½") bolts were made from SAE 4140 steel properly heat treated to a hardness of 30-33 Rockwell C. Since the metallurgical properties were satisfactory it is necessary to redesign the bolts if they are to be expected to withstand in combat the severe ballistic punishment to which they were subjected in the experimental tests. The bolts were sheared progressively, and, therefore, it is considered that each bolt should be made to absorb a greater proportion of the load by increasing the diameter.

The three-quarter inch (3/4") bolts were made from SAE 3140 steel properly heat treated to a hardness of 32 Rockwell C. The bolts were satisfactory from a metallurgical viewpoint, and consequently a redesign is necessary if they are to be expected to withstand the severe ballistic attack which was applied in the experimental tests.

4. The tests which were used to evaluate the metallurgical properties of these parts are as follows:

a. Chemical analyses.

b. Hardness surveys.

c. V-notch Charpy impact tests (of the shaft only).

d. Microscopic examination.

5. The results of the metallurgical examination of the trunnion shaft are as follows:

a. Visual Examination.

The shattered portions of the shaft which were submitted, see Figure 1, exhibit crystalline fractures throughout. The fracture appeared to have been initiated at the fillets on both sides of the flange.

b. Chemical Composition.

The engineering drawing requires that the shaft be made from heat treated SAE 4340 steel. The chemical analysis of the fractured shaft was that of SAE 6150 steel having the following analysis:

C	Mn	Si	S	P	Ni	Cr	Mo	V
.53	.80	.23	.037	.035	.20	1.02	.06	.16

The composition range of the SAE 4340 steel specified is as follows:

C	Mn	Si	Ni	Cr	Mo
.35/.45	.50/.80	.20/.35	1.50/2.00	.50/.80	.30/.40

The steel used has insufficient hardenability for 3" rounds when water quenched. The manufacturer undoubtedly attempted to attain the desired hardness by using the higher carbon SAE 6150 steel. The reduced alloy content, however, resulted in a substantial reduction in hardenability as compared to SAE 4340 steel. Although no experimental hardenability data was available, the approximate hardenability was obtained by using Grossman's data[1] of chemical composition versus hardenability. This data indicates that SAE 6150 steel would harden through approximately a 2" round when water quenched whereas SAE 4340 steel would harden through 3". The increased hardenability obtained by using a .50% carbon rather than a .40% carbon steel is not sufficient to warrant its use when the disadvantages such as susceptibility to quench cracking, slightly lower toughness, and increased residual stresses are considered. There are several steels available for application to 3" rounds which can be completely quench hardened. Examples are NE 9540, SAE 4340, and some of the NE steels treated with boron or addition

1. M. A. Grossman, "Hardenability Calculated from Chemical Composition" Metals Technology T.P. 1437, June 1942.

agents containing boron. To obtain the most from the alloy content involved, it is necessary to use a water quench, a practice which is almost universal among armor manufacturers. Oil quenching may be employed on higher alloy steels to achieve equivalent results. It might be noted that any of the steels used for making 2-3 inch thick rolled homogeneous armor could be employed for this application.

The use of steels containing over 3% alloy is not advised, for it has been observed at this arsenal[2] that many of these steels are susceptible to a temper brittleness phenomenon which cannot be eliminated when tempering temperatures below 1100°F are used. The specified hardness of 363 to 415 Brinell would result from a tempering temperature below 1100°F, and temper brittleness is, therefore, a factor which must be considered. Satisfactory properties can probably be obtained at a slightly lower hardness level (330-360 Brinell) by oil quenching the shaft from the tempering temperature.

c. Hardness.

Rockwell C hardness tests were conducted on a ground cross section of the fractured half section submitted. The hardness varied from Rockwell C 36 (332 Brinell) at the end to Rockwell C 29 (276 Brinell) at the center of the shaft, see Figure 2. The hardness of the flange was Rockwell C 41 (382 Brinell). In view of the wide variation in hardness obtained, it is obvious that the trunnion was not properly quench hardened. The hardness at the center was considerably lower than the 363 to 415 Brinell specified on the engineering drawing. The trunnion would be expected to withstand a great deal of punishment without deforming at a hardness level of 330 to 360 Brinell providing it was properly heat treated. Heat treating the trunnion to hardnesses over 360 Brinell is undesirable since the impact strength even after optimum heat treatment drops to 15-25 ft. lbs.

d. V-notch Charpy Impact tests.

Impact bars from the center and from the area adjacent to the circumference were broken at -40°F as well as at 68°F. Since it has been observed in armor plate studies[3,4] that the room temperature Charpy values and the drop in value between room temperature and -40°F indicate the tendency of a steel to exhibit brittle properties under ballistic tests. The results of the tests are as follows:

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2. WAL Report No. 710/678 "Cast Armor - The Development of Combinations of Compositions and Heat Treatments to Yield Optimum Shock Properties in Cast Armor 1" to 6" Thick", in preparation.

3. WAL Report No. 710/532 "Armor - Development of a Fracture Test to Indicate the Degree of Hardening of Armor Steels Upon Quenching", dated 1 August 1943.

4. WAL Report No. 710/534 "Armor Plate - Correlation of Metallurgical Properties with the Low Temperature Ballistic Shock Characteristics of 1" to 2" Low Alloy Cast Armor Tested at Camp Shilo" dated 16 August 1943.

	68°F			-40°F		
Area	Ft.Lbs.	Fracture	Hardness Rc	Ft.Lbs.	Fracture	Hardness Rc
Surface	8	Crystalline	34.0	5.5	Crystalline	33.5
	7.5	"	34.5	5.5	"	35.5
Center	6.5	"	31.0	5.5	"	32.5
	7.0	"	30.5	4.0	"	31.5
Surface*	9.5	"	34.0			
Retempered	9.5	"	33.0			

*Bars were retempered at 1125°F for 2 hours and water quenched.

The shaft exhibited very low impact strength as measured by the Charpy impact test even at normal temperatures. No improvement was obtained by water quenching from the temper, a treatment designed to eliminate any temper embrittlement which might be present. Properly heat treated steel having a hardness of Rockwell C 32-34 develops an impact value of 30 to 40 ft. lbs. at room temperature and reduction in impact value at the -40°F testing temperature does not exceed 10 ft. lbs.

e Microscopic Examination.

The examination of the unetched steel showed that the steel contained some segregation of nonmetallics, but they were not of such severity as to influence the toughness of the steel appreciably, see Figure 4A. Metallic segregation or banding was quite prominent in the longitudinal direction when etched in picral. Since the fractured surfaces of the trunnion shaft were completely crystalline, the effect of steel quality or directional properties were minimized. However in a shaft exhibiting sufficient toughness to deform during fracturing, the nonmetallic discontinuities would increase the resistance to deformation in the transverse direction. This trunnion was machined from bar stock and though it would tend to resist transverse cracking once started, the initial stages of cracking due to stress concentrations at the base of the flange would be more advantageously resisted by using an upset forging in which the flow lines run parallel to the fillet circumference. This effect is shown diagrammatically in Figure 3. Considerable saving in metal and maching time would be accompanied by this change in design. The microstructure of the shaft, see Figure 4, is a heterogeneous mixture of carbides, ferrite, and tempered martensite, the ferrite being more prevalent at the center than at the surface. The presence of very large carbides indicates incomplete carbide solution during austenitizing. As a consequence, the hardenability was impaired, and the quenched structure possessed a considerably larger amount of high temperature transformation products (ferrite and pearlite) than would otherwise have been the case. It was pointed out under the discussion on chemical composition that this steel possessed insufficient hardenability under the optimum conditions.

The poor microstructure is a result of a combination of insufficient hardenability, incomplete austenitizing, and possibly the use of an oil quench which is not an efficient quenching medium for heavy sections. However, an oil quench must in general, be employed in conjunction with 0.50% carbon steels.

6. The results of the metallurgical examinations of the bolts are as follows:

a. Visual Examination.

The ½" bolts connecting the turret to the upper base ring were sheared progressively during the ballistic tests. Two examples are shown in Figure 5. The 3/4" bolts submitted were deformed in the threaded portion but none were fractured. It was stated, however, in the ballistic report that several of these bolts were fractured. Examples of the 3" long and 1.4" long bolts are shown in Figure 5.

b. Chemical Composition.

The analysis of one of the ½" bolts and one of the 3/4"x3" long bolts is given below:

Part	C	Mn	Si	S	P	Ni	Cr	Mo	Type Steel
1/2" Bolt (#BAOX1)	.42	.80	.28	.029	.012	tr.	.97	.20	SAE 4140
3/4" Bolt (#BAPX1EW)	.37	.74	.34	.020	.018	1.22	.80	.09	SAE 3140

The alloy content in both bolts imparted sufficient hardenability so that they could be quenched to martensite in the section sizes involved.

c. Hardness Tests.

The hardnesses of the bolts are listed in the following table:

Type	Bolt No.	Rockwell C	Brinell (Converted)
BAOX1 (1/2")	1	34.5-33.5	310-320
	2	30.5-31.5	287-293
	3	29.0-29.5	275
BAPX1EW(3/4")	1	31.5-32.5	295-300
	2	31.5-32.0	295-300
A349490(3/8")	1	82 -84.5(Rb)	156-162

The first two types of bolts were hardened satisfactorily. A slight increase in hardness to Rockwell C 34-38 would be advantageous in increasing the tensile and shear strength without critically impairing the impact strength of these materials. The last bolt, however, (a short bolt which was of a different type) was not heat treated, and its hardness was considerably lower than is required in a bolt expected to carry its full share of the load.

d. Microscopic Examination.

The bolts were reasonably free from any undesirable segregations of nonmetallic inclusions. The distribution of the inclusions and the metallic banding indicate that both types of bolts were machined from bar stock.

The ⅝" bolts (BAOX1) and the 3/4" bolts (BAPX1EW) were heat treated to a tempered martensitic structure which would exhibit satisfactory impact strength commensurate with the hardness. One of the ⅝" bolts contained undissolved carbides and ferrite which are associated with incomplete austenitizing, see Figure 6B. Upon quenching and tempering this heterogeneous structure persisted, and the resulting hardness and impact strength of the bolt were impaired. It is necessary to hold the parts at the austenitizing temperature long enough for complete carbide solution to take place if the bolts are to be properly quenched to a homogeneous martensite having a uniform hardness upon tempering.

The 3/4" bolt (A349490) was probably annealed since it contained a heterogeneous structure of ferrite and pearlite. Either by design or accident this bolt was left in the dead soft condition. Any bolt which joins important armored sections of a tank must have a tensile strength high enough so that it carries its full share of the static load, and at the same time possess sufficient toughness so that it will not shatter under impact loading.

7. The trunnion shaft was subjected to severe impact stresses in the transverse direction under the ballistic impacts which exerted a large rotational force on the turret. The large inertia of the gun mount opposing the freely moving turret was transmitted through these trunnion shafts. Consequently the shaft was subjected to high impact stresses which were a maximum at the base of the flange. Since the shaft studied possessed poor impact strength, the ballistic attack resulted in a brittle fracture which was initiated at the base of the flange.

The impact properties of the trunnion shaft can be improved by a proper combination of analysis and heat treatment so that the shaft will possess sufficient toughness to prevent its being shattered under ballistic tests. Some plastic deformation may be encountered in a shaft with ideal metallurgical properties when the attack is extremely severe.

Satisfactory toughness can be attained in the shaft by employing a steel having sufficient hardenability for a 3¼" diameter round when water or oil quenched depending upon which is to be employed by the heat treater. The composition used (SAE 6150) possessed insufficient hardenability when water quenched, whereas the composition specified (SAE 4340) as well as several of the .40% carbon N.E. compositions can be satisfactorily heat treated when water quenched. A probable optimum combination of toughness and resistance to deformation can be obtained by tempering the part to a hardness of 330-360 Brinell. The toughness can be controlled by a V-notch Charpy impact test taken from the center of one shaft from each lot. A satisfactory minimum value at the above hardness level is 30 ft. lbs. at room temperature. There is some danger of the higher alloy steels (over 3% alloy) being susceptible to temper brittleness, and, therefore, it might be advisable to oil quench from the tempering temperature. Considerable saving in metal and machining time could be achieved by using an upset forging rather than the bar shock which was employed, and the shaft would possess better directional properties at the base of the flange where the stress concentrations are greatest.

If the above recommendations are successfully carried out, the trunnion probably will not break in a brittle manner when subjected to a severe ballistic attack, but, even with ideal metallurgical properties, the trunnion might deform under the stresses applied in this type of attack.

8. The one-half inch (½") bolts connecting the turret to the upper race ring were sheared off by the ballistic impacts against the turret wall. The bolts were made from properly heat treated steel having a hardness of 33 Rockwell C. However, since they were sheared progressively, it appears that each bolt did not carry a sufficient load to resist failure. The overall strength was lower than the force applied during the ballistic tests. Consequently the bolts should be of increased diameter, so that individual bolts will carry a greater lead in both shear and tension. The bolts can be hardened to 34 to 38 Rockwell C to increase the shear and tensile strength without critically impairing the impact strength, but they must be quenched to martensite before tempering to obtain the optimum impact strength. In changing the design, it may be necessary to change the composition of the steel to make certain that the bolts have sufficient hardenability so that they can be quenched to martensite during the heat treatment.

9. The three-quarter inch (3/4") bolts (BAPX1EW) were fractured probably because of excessive tensile and/or shear stresses encountered in the extremely severe ballistic test to which they were subjected. The bolts were satisfactorily heat treated to a hardness of 33 Rockwell C. If the cupola is expected to withstand the subject attack in combat without being separated from the turret it will be necessary to redesign the bolts so that they can withstand a greater load.

10. The three-quarter inch (3/4") bolt (A349490) was found to be in the annealed condition (dead soft). If this bolt and its companions are expected to carry a full share of the load, they should be heat treated to a hardness of 34-38 Rockwell C.

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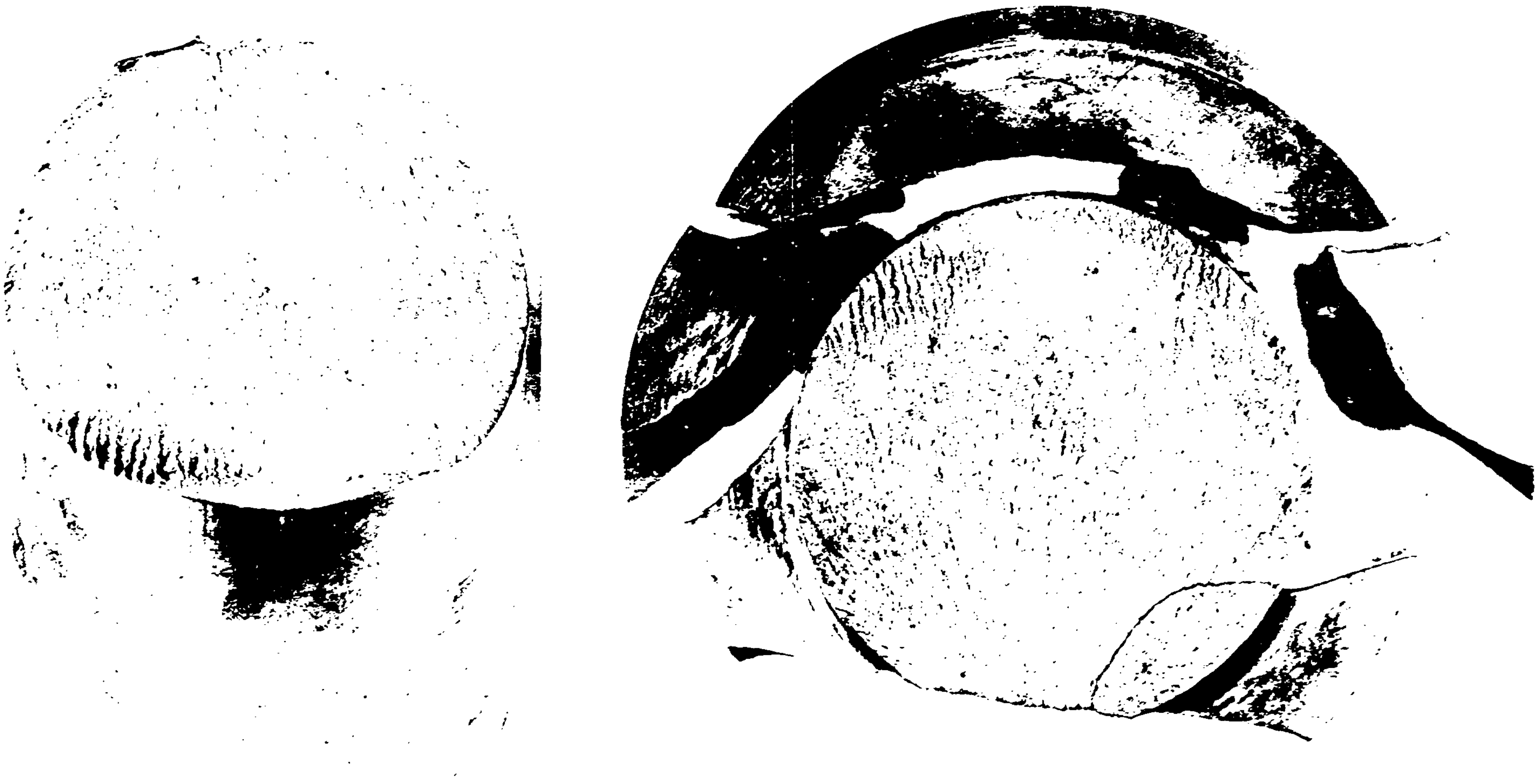

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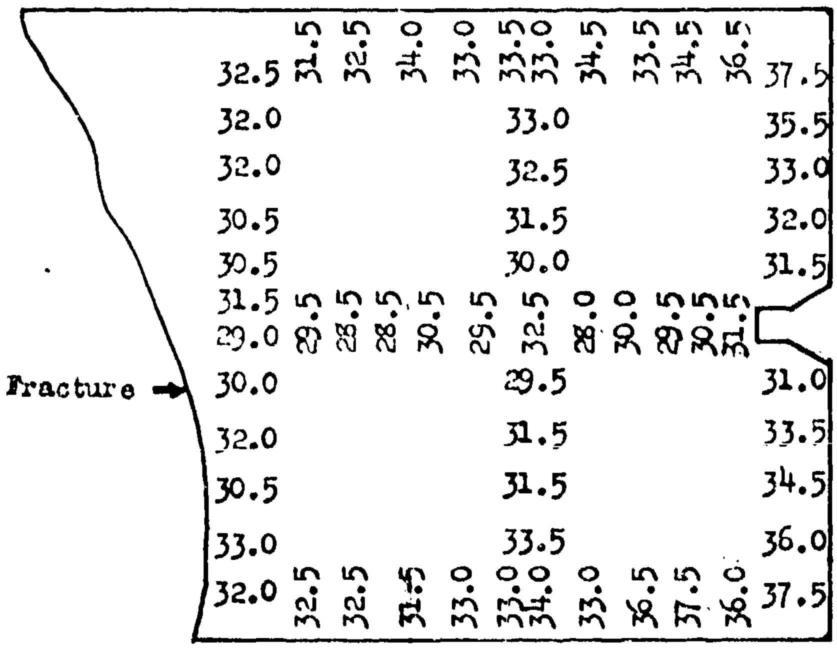
14 AUG 1944 TRUNNION PIN NO. B337185 WTN.720-730

FIGURE 1

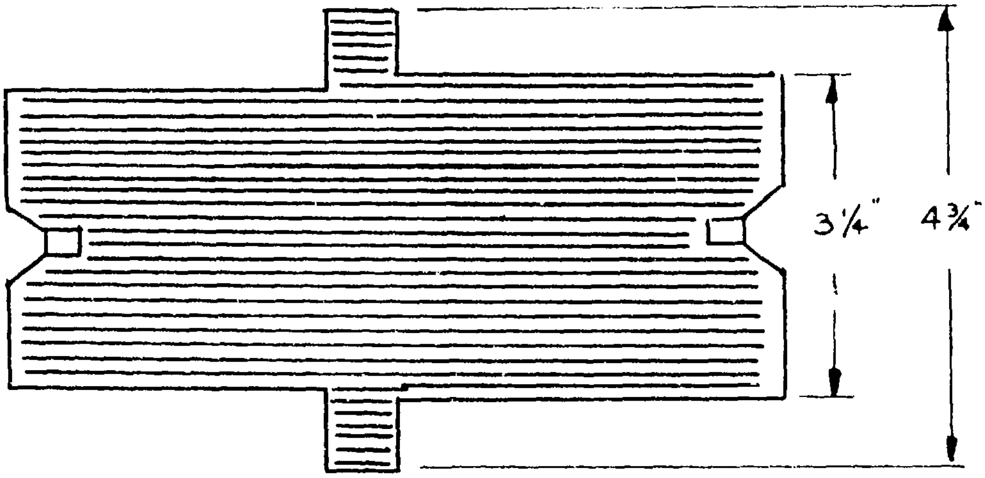


Rockwell C Hardness Results on
Cross Section of Trunnion Shaft

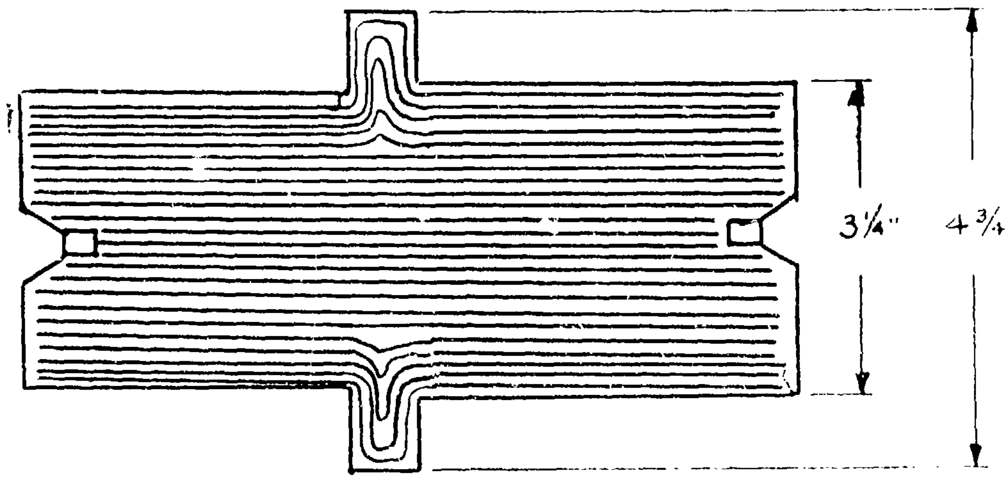
FIGURE 2

GRAIN FLOW IN TRUNNION SHAFT

(Cross Section Views)



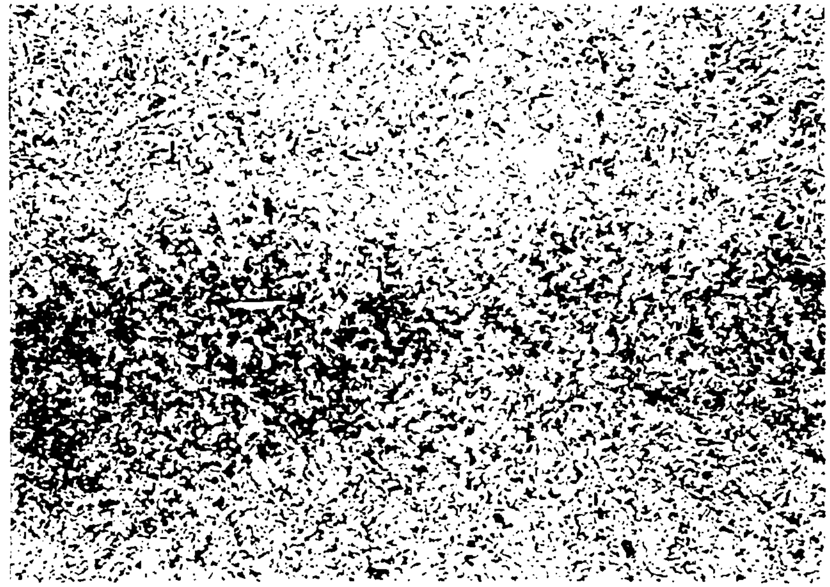
Present Design of Trunnion Shaft
Made from Bar Stock



Proposed Design of Trunnion Shaft
Made from Upset Forging

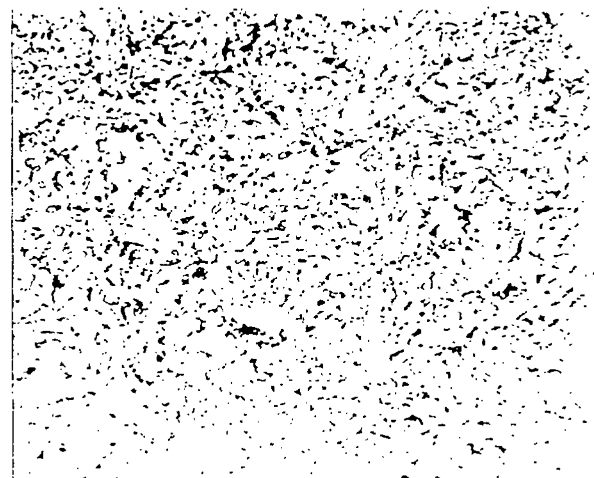
FIGURE 3

X100 -A- Unetched
Longitudinal direction. Nonmetallic segregations.



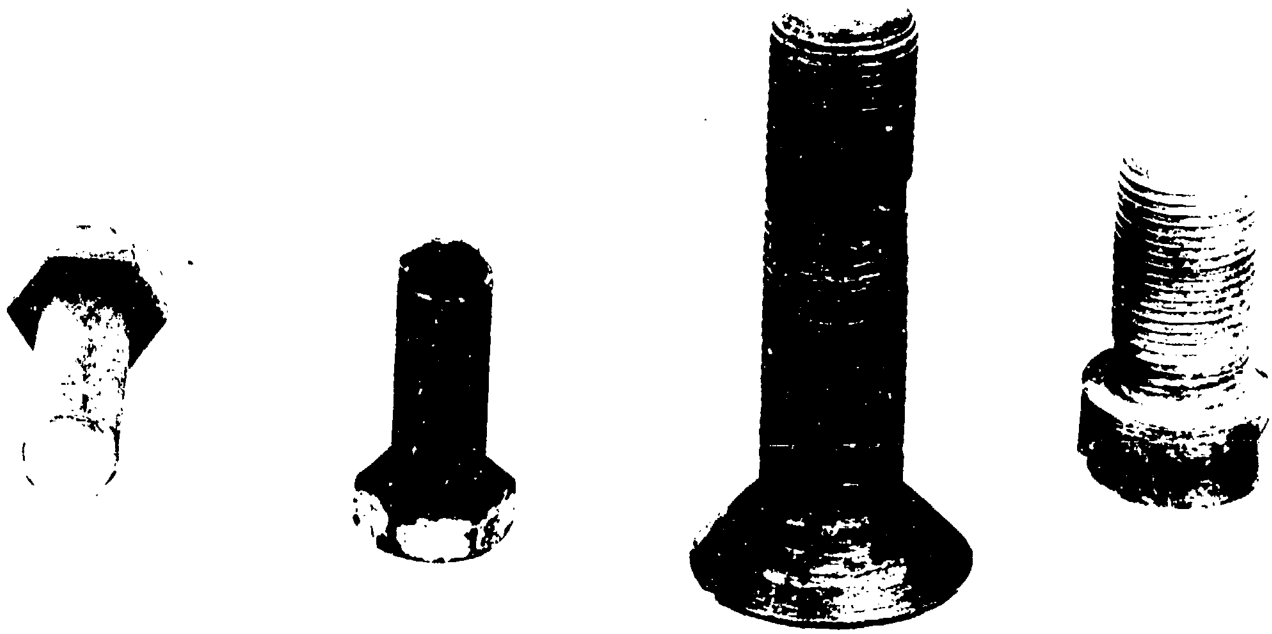
X250 -B- Picral Etch
Center - Banded area of ferrite, undissolved carbides and tempered martensite.

X1000 -C- Picral Etch
Surface - Tempered martensite, ferrite, and undissolved carbides.



X1000 -D- Picral Etch
Center - Ferrite, undissolved carbides with a small amount of tempered martensite.

FIGURE 4



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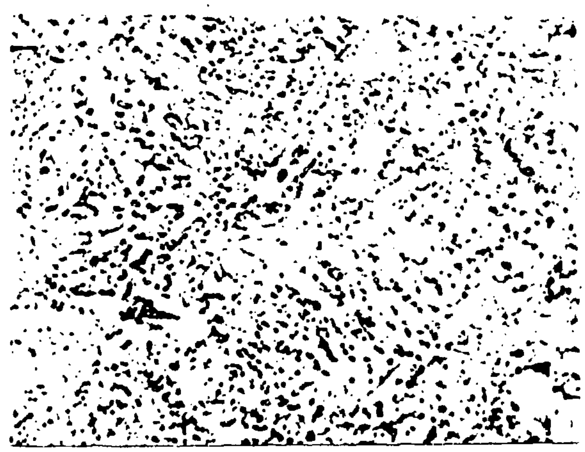
1/2" BOLTS ATTACHING TURRET TO UPPER BASE RING AND 3/4" BOLTS ATTACHING CUPOLA TO TURRET. 14 AUG 1944 WTN.720-729

FIGURE

Microstructure of Bolts

X1000 -A- Picral Etch
½" Bolt No. 1 Tempered Martensite



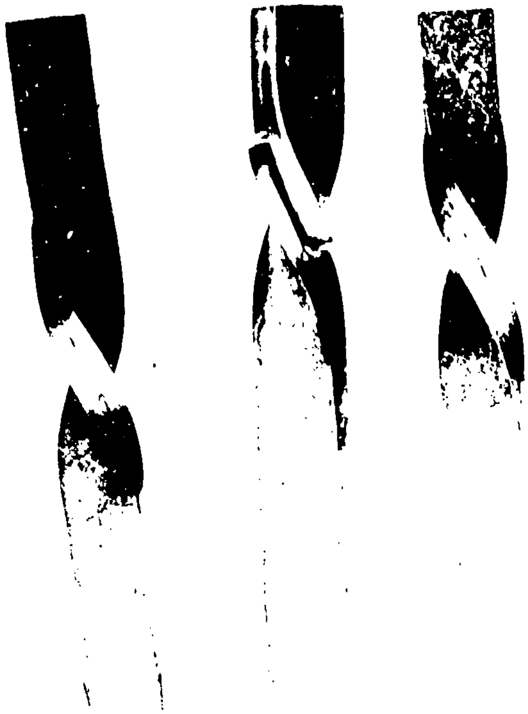
X1000 -B- Picral Etch
½" Bolt No. 3 Tempered martensite with undissolved carbides and ferrite.

X1000 -C- Picral Etch
3/4" Bolt (HAPXLEW) Tempered Martensite

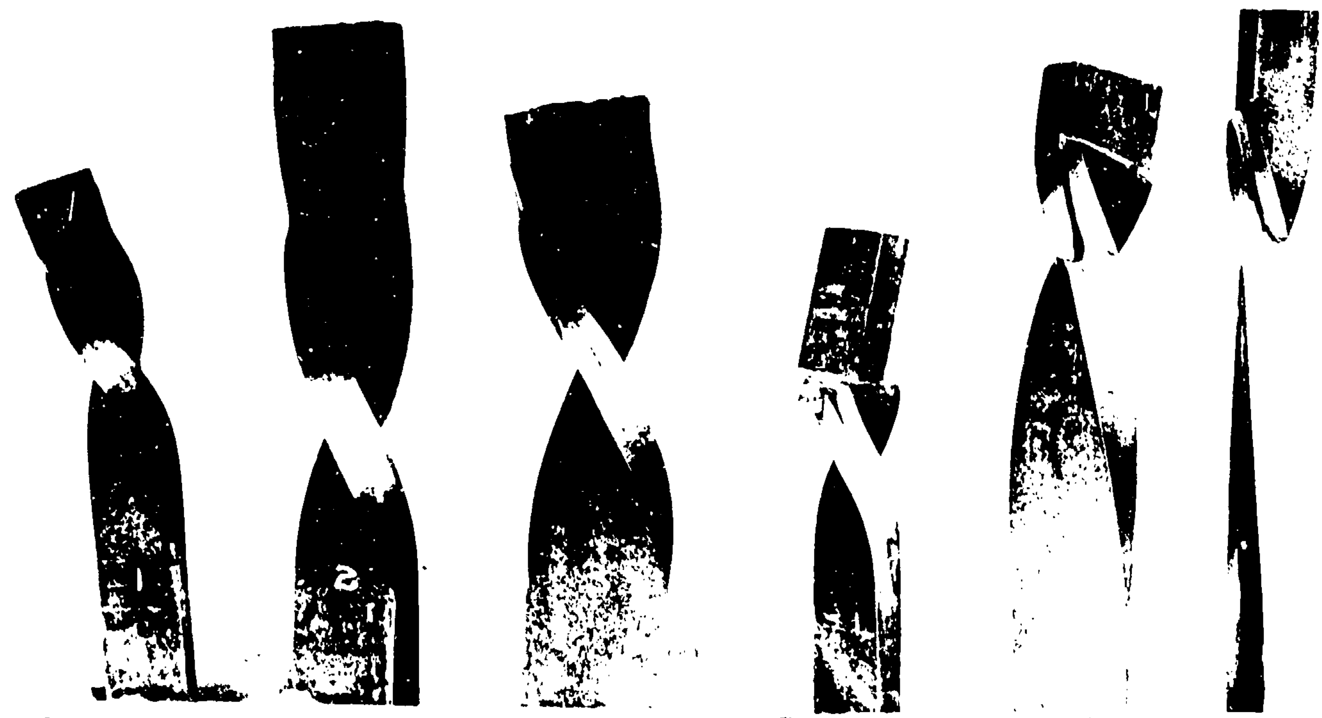
X1000 -D- Picral Etch
3/4" Bolt (A349490) - Annealed structure of pearlite and ferrite.

FIGURE 6

TORSION TEST



As Received X1
Nos. 1 and 3 - Longitudinal
No. 2 - Transverse

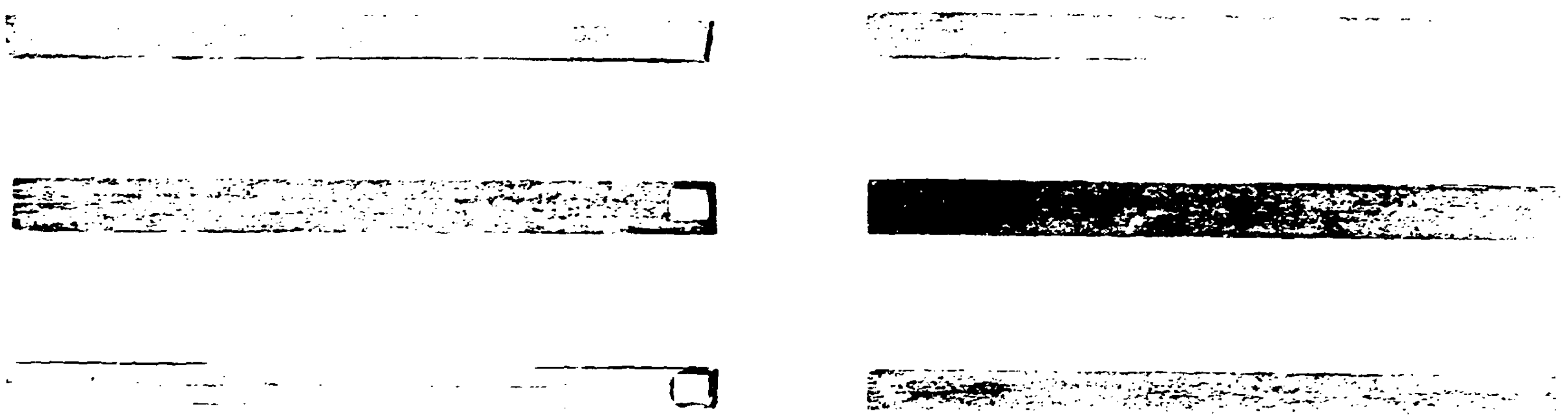


Longitudinal Tempered X1 Transverse Tempered X1

Sample No. 1 - 7/32" thick plate - spalled badly
No. 2 - 9/32" thick plate - spalled to a less degree
No. 3 - 7/32" thick plate - spalled badly

FIGURE 1

LONGITUDINAL TRANSVERSE

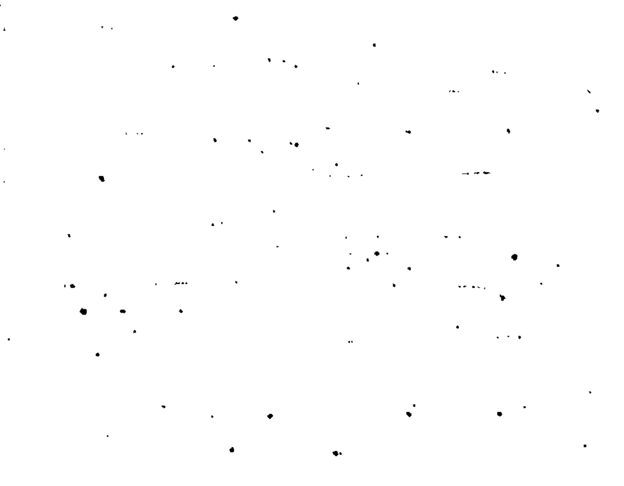


MACROSTRUCTURE OF SAMPLES FROM T16 UNIVERSAL CARRIER HULL

NO. 1 – 7/32" SPALLED BADLY
NO. 2 – 9/32" SPALLED TO SOME EXTENT
NO. 3 – 7/32" SPALLED BADLY

20 NOV 1944 MAG. X 1 WTN.710–2340

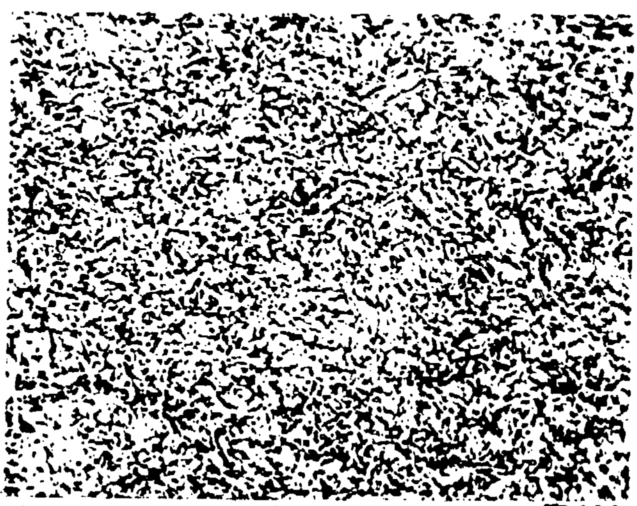
FIGURE 2



No. 1 Unetched X100
7/32" thick plate - spalled badly.

No. 2 Unetched X100
9/32" thick plate - spalled to a less degree.

No. 3 Unetched X100
7/32" thick plate - spalled badly.



No. 1 Picral X1000
Tempered martensite

No. 2 Picral X1000
Acicular tempored martensite.

FIGURE 3.