DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

AIR-HARDENING RIVET STEELS

By Harry K. Herschman

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 358

DEPARTMENT OF COMMERCE
BUREAU OF STANDARDS
George K. Burgess, Director

TECHNOLOGIC PAPERS OF THE BUREAU OF STANDARDS, No. 358
[Part of Vol. 22]

AIR-HARDENING RIVET STEELS

BY

HARRY K. HERSCHMAN, Assistant Metallurgist
Bureau of Standards

OCTOBER 19, 1927

PRICE 15 CENTS
$1.25 PER VOLUME ON SUBSCRIPTION
Sold only by the Superintendent of Documents, U. S. Government Printing Office
Washington, D. C.

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON
1927

T358

AIR-HARDENING RIVET STEELS

By Harry K. Herschman

ABSTRACT

A study was made at the request of the Bureau of Ordnance, War Department, of a series of alloy steels possessing air-hardening qualities for the purpose of determining their applicability for rivets which would have a ballistic resistance at least approaching that of the armor plate which they joined.

The steels selected for this study included for the most part those of the chromium-nickel series and some containing additions of manganese and molybdenum. In addition to the variation of alloy content, the carbon content was also varied, which permitted a study of the effect of each of these factors.

These steels were tested in the finished rivet form as well as in other ways—as, for example, the tensile test. The results pointed to the shear test as the best single indicator of the true value of any particular steel for rivet use. From this test a fair prediction, at least, could be made of the ballistic and impact properties of the various steels used.

The regulation of the carbon content is a very important factor in the make-up of alloy steel rivets. Small variations appear to affect materially the physical properties. There is an optimum carbon content for each particular alloy content which it appears can readily be determined by a shear test, together with hardness determination. The optimum carbon content for a 3.5 per cent nickel-1.5 per cent chromium steel was found to be about 0.20 per cent.

Steels containing a total of 4 to 6 per cent of the alloying elements, chromium and nickel, were found to produce excellent rivets. However, equally good results were obtained with steels of lower total alloy content by using in addition to chromium and nickel the elements molybdenum and manganese.

CONTENTS

I. INTRODUCTION

Light armor plate for tanks, airplanes, etc., can be made with quite satisfactory strength and ballistic properties. However, the use of ordinary rivet steels for joining armor plate leaves an "Achilles heel" in the armor due to the impracticability of heat treating such rivets after assembling to impart the desired strength and ballistic properties. It is obvious that a rivet which can be driven with reasonable ease and which on cooling will be harder and stronger than ordinary rivet steels is required. Air-hardening rivets naturally present themselves for such use.

The Bureau of Ordnance, of the War Department, recognizing the necessity for the development of rivet steels which, in assembled armor, would resist the penetration of bullets as well as the armor which the rivets joined, requested the Bureau of Standards to study the applicability of air-hardening steels for use as rivets for armor assembly.

While the work described herein was done primarily for the War Department in conjunction with armor-plate research, the tests made and the results obtained therefrom may be useful in determining the suitability of the steels described for purposes other than armor construction. This report is published with the permission of the War Department.

II. LIMITATIONS OF ORDINARY RIVET STEELS

Rivets of ordinary carbon steel have a tensile strength of 50,000 to 60,000 lbs./in.^{2}, while those of 3½ per cent nickel steel have 75,000 to 100,000 lbs./in.^{2} tensile strength. These give, in the double-shear test on finished joints, 35,000 to 45,000 lbs./in.^{2} and 50,000 to 70,000 lbs./in.^{2}, respectively. They have Brinell hardnesses of 100 to 200 with a pearlitic structure and inferior ballistic resistance.

Such rivets, used for structural, bridge, or ship work, are comparable in properties to the steels with which they are used. In cases such as the present, where good ballistic resistance is sought and where even at best it can scarcely be hoped that the rivets can have as good ballistic resistance as the plates they secure, the fewer the rivets necessary in the preparation of an efficient joint the better the structure. The fewer the rivets the less is the cost for punching and driving. It is not unlikely that, even in structures other than tanks, the use of stronger rivets, to reduce the number used, might result in economy.

In Table 1 are shown the compositions of a series of carbon and nickel steels, together with the mechanical properties of these steels in the pearlitic condition. These values would closely approximate those which would be expected when such steels were in the finished rivet form.

TABLE 1.—*Mechanical properties of steels of various compositions in pearlitic condition after air cooling*

Composition		Treatment air cooled from—	Proportional limit	Yield point	Tensile strength	Elongation 2 inches	Reduction area	Brinell
C	Ni							
Per cent	*Per cent*	° *C.*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Lbs./in.*^{2}	*Per cent*	*Per cent*	
0.12	----------	----------	35,000	----------	50,000	45	72	[1] 95
.34	----------	[2] 820	42,000	43,000	77,500	34	57	155
[3].60	----------	[2] 820	65,000	91,000	133,500	15	45	270
.75	----------	[2] 750	55,000– 65,000	----------	125,000– 128,000	15½	23– 26	250
.33	3.00	[2] 780	----------	74,000	95,500	22½	47	185
.60	3.00	[2] 780	46,000	112,000	146,000	10	38	270

[1] By special heat treatment this steel may be obtained at 80,000 tensile, 15 per cent elongation, 155 Brinell, cold driving being necessary in order to retain the properties imparted by the heat treatment (see "Some physical properties of low-carbon steels," by R. H. Smith, Trans. Am. Soc. Steel Treating, 7, No. 5, p. 569).

[2] Riveting temperature (approximately), 1,100° C.

[3] Also contains 1.20 per cent silicon.

NOTE.—These figures are taken from various sources and refer to air cooling of sizes other than those met in rivet practice. The hardness of these is too low for good ballistic resistance.

For the purposes in view the combination of high hardness, strength, and toughness, coupled with a fair degree of ductility, is required. For ordinary purposes such a combination would be obtained by the use of one of a variety of alloy steels and by heat treating; quenching in water or oil for full hardening to martensite (which is relatively hard and brittle), followed by reheating (drawing or tempering) to break the martensite down into troostite or sorbite (which are softer and tougher). However, the heat treatment of an assembled tank or any large part of such a structure is difficult and inconvenient, so that the properties desired in the rivets must be sought by other means.

It is not fully clear to what extent the factors of hardness and toughness affect ballistic resistance. A fully hardened martensitic structure of 550 to 600 Brinell is quite certain to be too brittle. A fully sorbitic structure having a Brinell of 300 to 350 is probably too soft. A partly tempered martensite with a Brinell number within the range 375 to 425 is probably close to the optimum for ballistic resistance. Such steels will have, roughly, a tensile strength of 200,000 lbs./in.^{2}, with 10 per cent elongation.

To obtain these properties or any near approach to them without quenching in a liquid and subsequently tempering, it is necessary to use a steel that is at least partly air hardening; that is, one that will produce martensite on cooling in air.

At riveting temperatures steels are austenitic. At a relatively slow cooling rate as in a cooling rivet, the austenite of a carbon steel changes to ferrite and pearlite just as it does in free-air cooling. If the cooling rate is increased as by a mild quenching, the change to ferrite and pearlite is suppressed, and instead two other changes take place, austenite going to (primary) troostite or to martensite or to both. As the cooling rate is increased there is less troostite and more martensite, till finally the product is practically all martensite. With an extremely rapid cooling rate not all the austenite goes to martensite, but some will be retained as such.

Martensite varies in properties with the composition of the steel. In a high-carbon steel the martensite is very strong, very hard, and very brittle, and the steel is unable to resist shock. With lower carbon, the martensite is still relatively hard but not quite so brittle.

While no reheating is practicable after riveting has been completed, it is not impossible that some decomposition of martensite may take place. If it is formed at a high enough temperature, one at which it is not stable, it changes over, in part, to (secondary) troostite and sorbite, if cooling below that temperature is sufficiently slow.

In an alloy steel of given carbon content a desired type of microstructure after cooling may be obtained either by changing the cooling rate, by changing the amount of alloying elements, or by changing the temperature from which the steel is cooled. An increase in carbon content acts somewhat like an increase in alloying elements.

In a rivet the cooling rate is fixed. The mass of the rivet and of the plates it joins together with their heat conductivities establish the cooling rate of the rivet. The maximum temperature of the rivet may be varied somewhat but is relatively fixed. The only real control in securing the desired microstructure is, then, in the chemical composition. This must be balanced against the cooling rate of the particular rivet. Hence, the best composition need not be the same for different sizes of rivets which have different cooling rates.

It is obvious that steels for the purpose in hand must be dominantly martensitic, else the needed hardness and strength will not be obtained. Steels of apparently 100 per cent martensitic structure have a Brinell hardness varying from as low as 350 up to as high as 700, with very similar microstructures. The toughness of these true or pseudo martensites will usually vary inversely as their hardness. The lower the carbon and alloy content the lower the hardness and the greater the toughness.

Some degree of toughness might be obtained by securing, instead of a pure martensite, a mixture of martensite and (primary) troostite or, possibly, one of martensite and austenite, the latter mixture (plus free carbides) being found in high-speed tool steel. It is difficult, however, to obtain just the same mixture twice in succession. Accidental variations of composition or cooling rate will change the proportions in the mixture, and it would hardly appear feasible to depend on getting toughness by obtaining very much primary troostite or very much austenite. The steels which would retain austenite would be expensive because of the high alloy content required.

Some toughness might also be obtained by using a steel which at the cooling rate employed would produce the change to martensite at such a high temperature that some of this martensite would break down, in part, on further cooling to (secondary) troostite or even to sorbite. These are tough, and the mixture with the undecomposed martensite could have both hardness and toughness. Hence, the temperature at which the martensite transformation takes place has to be considered.

Austenite shrinks on cooling at an approximately uniform rate. When it changes to martensite the steel increases about 1½ per cent in volume. After the transformation is complete the martensite will then shrink on cooling. Just when and how these size changes take place on cooling will, of course, affect the tightness of the rivet. Cracking of the rivet or the setting up of internal stresses by the volume change at the transformation will depend on the plasticity of the steel at the transformation temperature.

The effects of all of these factors on the properties of the finished rivet must be considered, but for the present it can be assumed that what is needed is a steel which will give an almost wholly martensitic structure. On this assumption, the properties of the rivet must be obtained by adjusting the composition to give the type of martensite needed. If the further assumption that a tough and not a brittle martensite is needed is correct, then the carbon must be kept low, and the martensitic structure and the degree of hardness needed must be obtained by using fairly generous amounts of alloying elements.

III. CHOICE OF STEELS

The commonly used elements which strongly affect the critical cooling rate of steels are manganese, nickel, chromium, tungsten, and molybdenum. In a 0.25 per cent carbon steel it requires about the percentages shown in Table 2 to make the steel martensitic, or at least to prevent it from being pearlitic, on air cooling. The approximate costs per pound of the elements are also given.

TABLE 2.—*Approximate percentages and market prices and sources of some alloying elements used in the production of air-hardening steels containing 0.25 per cent carbon*

Alloying element	Approximate percentage needed for martensite in a 0.25 per cent carbon steel	Cost per pound [1]	Source
Mn	5½	\$0.065	Ferromanganese.
Ni	10	.35	Metal.
Cr	7	[3] .23	Ferrochromium.
W	[2] 8	.95	Ferrotungsten.
Mo	[2] 2	1.25	Calcium molybdate.

[1] Based on market prices of May, 1927.

[2] Structures no longer pearlitic, but not necessarily fully martensitic. Special carbides are formed.

[3] Low-carbon ferrochromium.

By using two or three of the alloying elements shown in Table 2 the total amount needed to make the steel martensitic is greatly decreased. The effect of a second or third alloying element may not be merely additive, but intensifying. Tungsten and molybdenum are especially strong intensifying agents, and while the base air-hardening steel will doubtless be made up of the cheaper elements—manganese, chromium, and nickel—the use of a little molybdenum or tungsten (probably molybdenum, as it is more effective than tungsten and hence the cost for the amount required is lower) should also be considered.

Steels containing sufficient of only one of the elements manganese, nickel, or chromium, so that they are martensitic, are inclined to be brittle in the air-hardened condition. Most existing data on such steels refer to those rather high in carbon, however.

Charpy [1] states that air-hardening steels were satisfactorily used for rivets in France some 20 years ago, but he does not give details.

The literature of air-hardening steels is fairly extensive, but deals chiefly with steels of relatively high-carbon content, intended to be tempered, and there is little that can be used as a direct guide for rivets. It is well known [2] that the proportional limit of such steels is low, probably due to internal cooling stresses; but slight distortion raises the proportional limit, and a set of a few thousandths of an inch per inch would not be expected to be harmful in a tank rivet, though it would be in a crank shaft made of such steel. The tendency of these steels to be brittle under shock, especially when the steel parts contain notches, is another drawback. This will require the avoidance of sharp corners in the design of the rivets.

The application of air-hardening steels to rivets is a new departure. No one seems to have made a systematic search for steels combining hardness and toughness in the air-cooled condition without tempering, so the whole problem has had to be attacked experimentally. From the engineering point of view the questions to be asked about an air-hardening rivet steel are: (1) Will it rivet satisfactorily? (2) Are the joints strong? (3) Do the rivets resist projectiles? From the metallurgical point of view the further questions may be asked: (1) What alternative types of steels can be used? (2) In any given type, what limits of composition must be set?

IV. STEELS USED

In carrying out the preliminary work of this investigation five nickel-chromium steels known to be air hardening were selected. These were to have a total alloy content of 5 to 6 per cent, as shown in the table following.

---

[1] Charpy, G., "Use of special steels for riveting," Comptes Rendus, **143**, p. 1156; 1906.

[2] Aitchison, L., "The low apparent elastic limit of quenched and work-hardened steels," Iron and Steel Inst. (London), Carn. Sch. Mem., **12**, p. 113; 1923.

Carbon	Nickel	Chromium
0.25	2.5	2.5
.25	2.5	3.5
.25	3.5	1.5
.55	3.5	1.5
.25	4.5	1.5

The actual composition of these five steels as received is shown in Table 3, listed as first series of steels.

TABLE 3.—*Chemical composition of steels used*

FIRST SERIES OF STEELS

Specimen	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium	Nickel
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
A	0.23	0.33	0.014	0.020	0.20	1.48	3.83
B	.28	.50	.030	.040	.44	2.44	2.40
C	.25	.59	.024	.030	.20	1.54	4.55
D	.35	.57	.020	.041	.27	3.67	2.69
E	.42	.53	.019	.044	.16	1.35	3.51

SECOND SERIES OF STEELS

Specimen	Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium	Nickel	Molybdenum
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
54	0.04	0.51	[1] 0.01	0.012	0.17	1.12	3.66	---------
56	.10	.51	[1] .01	.011	.11	1.82	3.31	---------
57	.20	.68	[1] .01	.012	.33	.97	3.84	---------
58	.25	.50	[1] .01	.012	.16	1.48	1.84	---------
68	.17	.72	[1] .01	.015	.12	1.16	3.38	---------
925	.26	1.00	.029	.015	.37	---------	---------	1.22
926	.25	.82	.021	.020	.37	.78	---------	.81
927	.33	.92	.022	.019	.31	.62	1.41	.49

[1] Less than 0.01 per cent phosphorus.

This series was later supplemented by another series in which the steels contained two or more of the following elements: Nickel, chromium, molybdenum, and manganese. This series was made at the Bureau of Standards.[3] Compositions were chosen which would allow study of the effect of varying the carbon content. The compositions of these steels appear in Table 3 under the heading "second series of steels."

V. TESTS AND PROCEDURE

1. RIVETING PROPERTIES

It is well known that all these steels when heated so that they are austenitic are forgeable. Obviously they can be riveted. Laboratory tests were made in an attempt to obtain quantitatively an idea of the differences in riveting properties of each steel.

---

[3] These steels were made by T. G. Digges, of the Bureau of Standards.

The various steels of Table 3 (first series) were held at 900, 1,000, 1,100, and 1,200° C., and the deformation noted of a special test piece under the impact of a single blow having an energy input of about 230, 450, 560, 800, and 1,150 foot-pounds. Five chromium-nickel steels were compared with carbon steels of 0.10 and 0.23 per cent carbon. These tests indicated that there was very little difference among the steels. This indication was interpreted as being in line with the work of Robin,[4] but any such conclusion has had to be discarded, because in driving actual rivets of the nickel-chromium steels it was noted that they did not rivet as readily as ordinary carbon steel rivets. No figures can be given as to the increased time necessary in riveting. This latter factor could best be determined on a production job. However, the nickel-chromium steel rivets can be driven without difficulty and their greater resistance to flow at riveting temperatures is not sufficient to hinder their use.

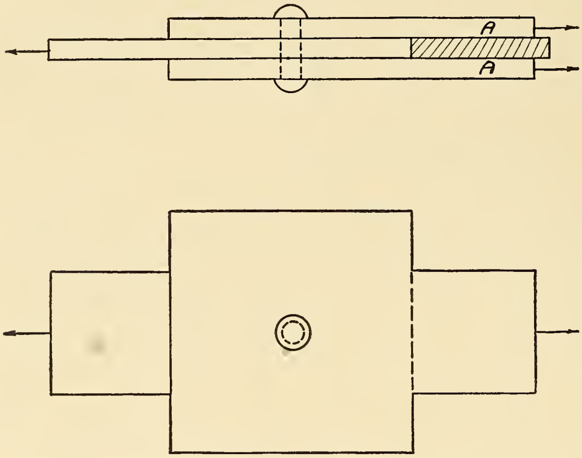


Fig. 1.—*Type of joint used for shear tests of rivets*

2. SHEAR TESTS

Three half-inch plates of 0.30 per cent carbon, 3.50 per cent nickel steel, oil quenched from 840° C. (1,550° F.), drawn at 425° C. (800° F.) were riveted as shown in Figure 1. The holes were bored before heat treating. For the half-inch diameter rivets, which had shanks only 1 inch long after heading, the outer plates were counterbored to a depth of one-fourth inch. This was not done on the three-fourths-inch diameter rivets which had 1½-inch shanks after heading.

The rivets were driven by a pneumatic bull,[5] the heading thus being done by a pressing action instead of by repeated blows. The rivets were inserted into the plates at about 1,150° C. (2,100° F.), the pressure being kept on till the rivet was at about 600 ± ° C. (1,110° F.). All joints were found to be tight and secure.

In testing, a piece of plate (shown crosshatched in fig. 1) was inserted to prevent the testing machine grips from squeezing the two

---

[4] Robin, F., "Resistance of steel to crushing," Iron and Steel Inst. Carnegie School Mem., **2**, p. 70; 1910.

[5] All riveting was done at the Naval Gun Factory in Washington.

outer plates together. The tests were made in a 200,000-pound capacity testing machine by using wedge grips. Although an effort was made to determine the breaking load in addition to the maximum load, it was found impracticable to obtain it, as fracture occurred either too soon after the maximum load was reached or at an indeterminate period due to the rivet suddenly deforming before fracturing.

Figure 2 shows the general manner in which the rivets fractured in the shear tests.

3. TENSILE TESTS ON FINISHED RIVETS

Two rings (*AA*, fig. 3), each 1¾ inches high by 1¾ inches (outer) diameter, were riveted together as shown in Figure 3. The rings were threaded for screwing into special holders for the testing machine, thus allowing a tensile test of a finished rivet. The shank length used was longer than that which would be used in riveting light armor plate. The rate of cooling was doubtless different from that met in the tank riveting, because the thickness of the riveted mass was greater in the former, while the cross-sectional area of the riveted mass was less. These longer rivets will contain more heat to be dissipated than a shorter one, and the middle of the rivet probably cools more slowly than in the case of the more practical-sized rivets, such as were used in the shear test.

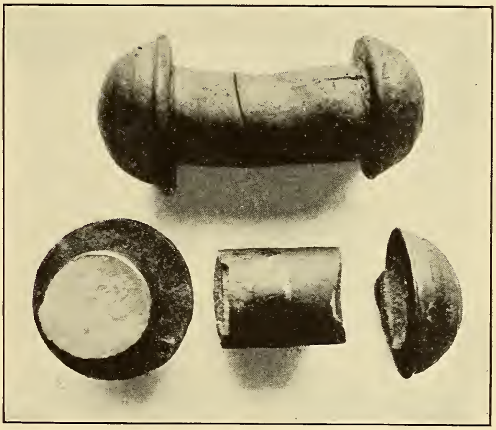


FIG. 2.—*Appearance of rivets after shear tests*

The rivets were inserted at approximately 1,150° C. (2,100° F.) and driven by a pneumatic bull. Not all of these rivets were tight. This will be commented on later, when consideration of rivet strength has been completed.

4. REGULAR TENSILE TESTS

A further comparison was made on standard tensile test bars. Ordinary 0.505-inch diameter 2-inch gauge length tensile specimens were air cooled after heating one hour at 1,100° C. (2,010° F.). The rate of cooling for such specimens is not necessarily the same as is met in the actual cooling of rivets in tank plates. In testing these specimens a Berry strain gauge was used to obtain the stress-strain relations.

5. EXPANSION BEHAVIOR AND TESTS

As has been previously stated in the preparation of specimens for tensile tests on finished rivets, it was found that some of the joints loosened after cooling to room temperature. These tensile tests were made especially for determining the possibility of "head popping" in rivets made of air-hardened steels. Such effects would be expected if sufficiently high contraction stresses were set up in these steels during cooling. Instead of a shrinkage of the shanks to a degree sufficient to draw the heads so tight against the plates as to cause the heads to snap, a condition quite to the contrary was created, thus resulting in a failure to produce a sufficiently tight fit.

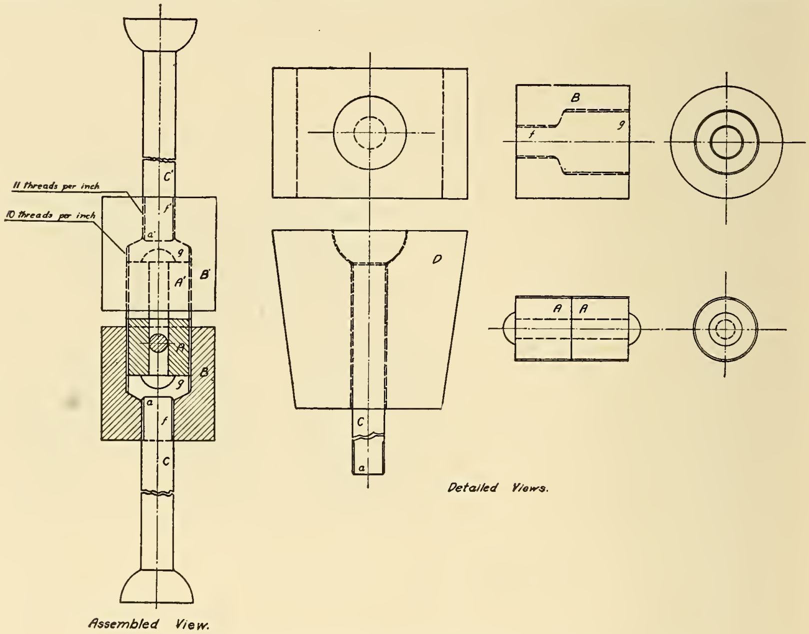
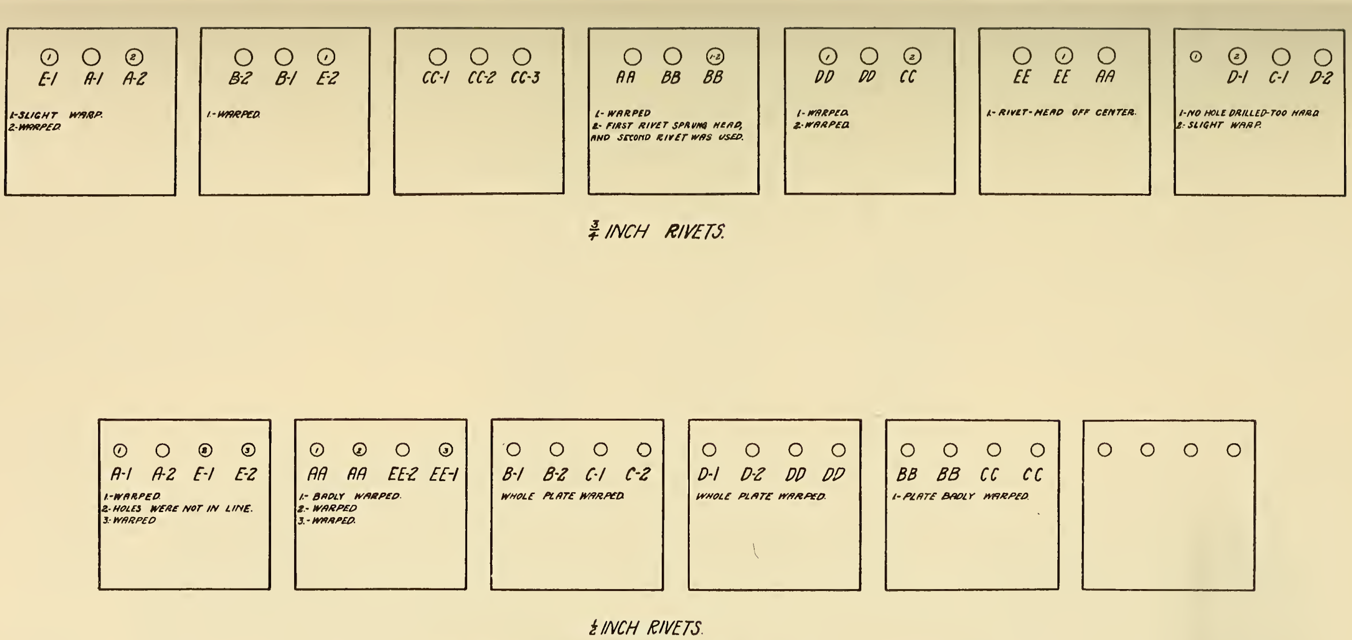


Fig. 3.—*Apparatus used for tensile tests of finished rivets*

In some cases the two rings *AA* in Figure 3 could be twirled about on the rivet shank after cooling, although they were tight when the pressure of the "bull" was released and for some time thereafter and became loose at a few hundred degrees centigrade above room temperature; that is, when the expansion due to the change of austenite to martensite took place.

These rivets with very long shanks probably did not upset quite as much in the shank as in the case of the shorter rivets used in the shear tests. No rating of the steels on the basis of tightness (or looseness) of the finished rivets of Figure 3 could be made, as quantitative measurements were not practicable and recourse had to be had to other tests.



CHEMICAL COMPOSITION (IN PERCENT).

RIVET	CARBON	MANGANESE	PHOSPHORUS	SULPHUR	SILICON	CHROMIUM	NICKEL
A&AA	0.23	0.33	0.014	0.020	0.20	1.48	3.83
B&BB	0.28	0.50	0.030	0.040	0.44	2.44	2.40
C&CC	0.25	0.59	0.024	0.030	0.20	1.54	4.55
D&DD	0.35	0.67	0.020	0.041	0.27	3.67	2.69
E&EE	0.42	0.53	0.019	0.044	0.16	1.35	3.51

NOTE: PLATES AS SHOWN REPRESENT ARMOR PLATES WHICH WERE RIVETED TO SOFT PLATE WHICH SERVED AS BACKING.

Fig. 4.—*Chart showing arrangement of rivets in plates for ballistic tests*

Single letters as *E* indicate square shouldered rivets. Double letters as *EE* indicate bevel shouldered rivets

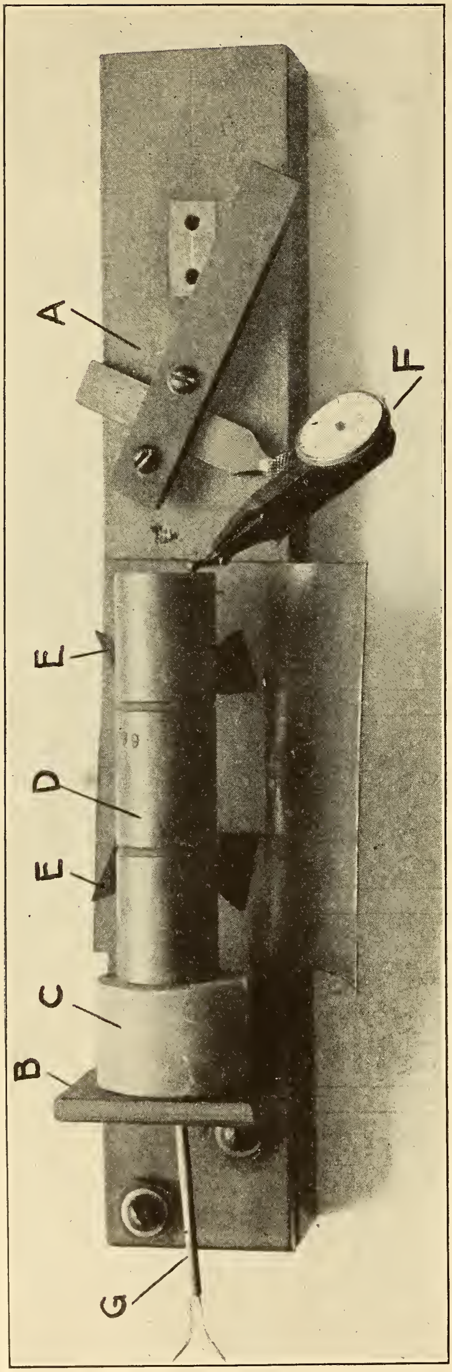


FIG. 5.—*Dilatometer or expansion apparatus*

These were made by using the crude dilatometer shown in Figure 5.[6] The specimen used was a 4 inch by $\frac{3}{4}$ or 1 inch diameter bar with a $\frac{3}{32}$-inch hole drilled 2 inches deep in one end so a thermocouple could be inserted at the center. Specimens were held at 900° C. (1,650° F.) for 15 minutes, plunged in oil for 10 to 15 seconds (according to the size) to cool them somewhat, but not past the transformation temperature, Ar''. The cylinder was placed on the supports *E*, against the refractory block *C*, through which the thermocouple *G* passed into the center of the specimen *D*. The base *A* and the projection *B* were rigid. A "last word" micrometer dial was actuated by the lever arm which rested against the end of the specimen. As the specimen air cooled, the temperature was given by the thermocouple and the change in length by the dial.

6. THERMAL ANALYSIS

The inverse-rate method was employed in the determination of the transformation temperatures of the steels, the specimens being cooled at a uniform rate, and records of the time made for each temperature change of 2° C. A complete description of the procedure for this test has been given.[7]

---

[6] The dilatometer used in these tests was devised by H. Scott, formerly with the Bureau of Standards.

[7] Scott, H., Use of Modified Rosenhain Furnace for Thermal Analysis, B. S. Sci. Paper No. 348; October, 1919.

7. HEAD-FLATTENING AND BEND TESTS

Two of the important tests in the generally accepted specifications for rivet steels are the head-flattening and the bend tests. The current specifications require that such tests be carried out on both hot and cold specimens. However, these requirements refer to "plain" carbon steels, and it would obviously be incorrect to require alloy steels of composition similar to those used in this investigation to pass the "cold tests." If they did, they would not resist projectiles. The "hot tests" were accordingly used exclusively.

The specimens for the "head-flattening" tests consisted of ½ and ¾ inch button-head rivets, which were heated to about 1,100° C. (2,010° F.) and the heads subjected to blows of a trip hammer, applied at right angles to the axis of the rivet. The flattened head so produced did not exceed one-quarter the original thickness of the section before forging. Figure 6 shows the specimens both before and after flattening. Specimens showing no cracks after this test are considered as passing the test.

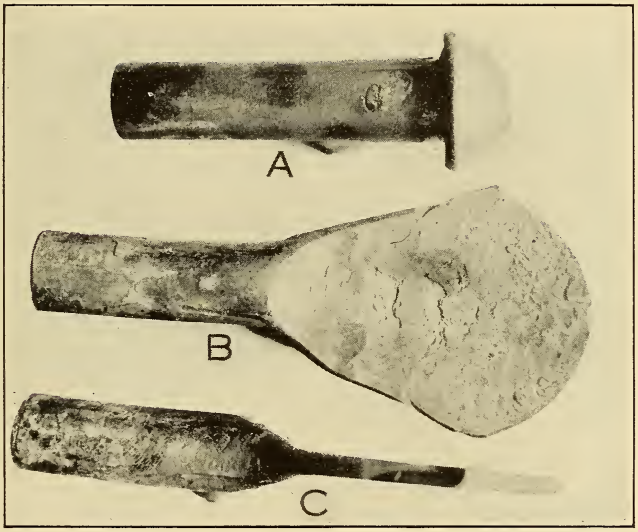


Fig. 6.—*Rivets subjected to head-flattening tests*

A, Rivet before test.
B, Face of rivet hammered after test.
C, Section showing reduction of head after test.

The bend-test specimens consisted of ½ and ¾ inch round bars of annealed steel measuring 4 and 5 inches in length, respectively. These were heated to about 1,100° C. (2,010° F.) and bent through 180°, as shown in Figure 7. These were examined on the convex portion of the bend for presence of cracks or other defects produced by bending.

8. BALLISTIC TESTS ON RIVETS

Thirteen riveted joints were made up, as indicated in Figure 4, by using four ½-inch and four ¾-inch rivets of each of the five compositions given in Table 3 (first series). The ½-inch rivets were used on joints made of two ½-inch plates, one being hardened armor plate while the other was of mild carbon steel and acted as a soft backing for the armor plate. The joints on which the ¾-inch rivets were used were made in a manner similar to the above-described joints, except that ¾-inch plates were substituted for the ½-inch plates.

As previously pointed out in this report, internal stresses may be set up in the rivet by the square shoulders formed at the junction of the head and shank, which may, in turn, cause a failure of the rivet. Thus, in order to prepare for a fair test of these rivets two of each of the sets of four holes drilled were countersunk with a 45° drill, thus eliminating the square shoulder on the rivet.

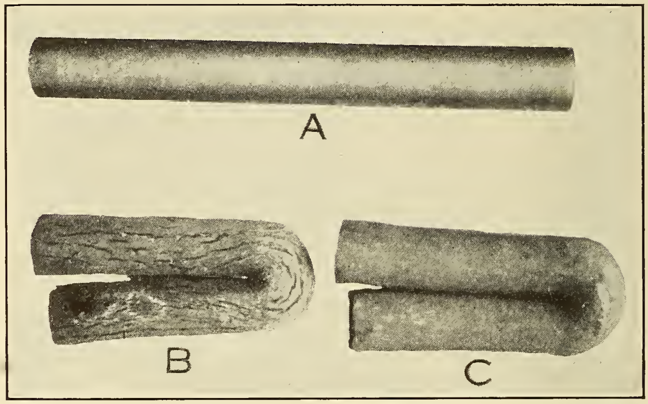


Fig. 7.—*Specimens subjecied to bend tests*

A, Specimen before test.
B, Specimen after test (deep etched in hot hydrochlorid acid).
C, Same as *B* (unetched).

All bullets used for the ballistic test[8] were .30 caliber. The first eight charges were specially made up with variable powder contents while the following four were regulation service charges. The striking velocities of these first 12 projectiles were calculated by a special chart method. After these preliminary tests it was decided to use the service-charge bullet on all tests without determining the velocity for each test, the initial tests having shown the bullets to have an average striking velocity of 2,650 feet per second.

---

[8] Ballistic tests were made at the Aberdeen Proving Ground.

VI. MICROSTRUCTURE AND HARDNESS TESTS

It is evident that a material increase in strength of alloy steels over that of mild carbon steels must necessarily be accompanied by an increased hardness. However, the degree of increase in hardness must be limited to avoid the dangerously brittle range. While a steel containing martensite is desired, yet one which is purely martensitic will have a low impact resistance and would obviously be valueless for rivet use, especially in armor plate Thus, it is necessary so to balance the carbon content of the steel against the alloy content as to obtain the optimum hardness. Accordingly, a series of steels of fixed nickel and chromium content and variable carbon content was prepared and the shear strength determined. These results, together with the hardness values, determine the proper proportion of carbon for the maximum producible shear strength for a fixed alloy content. The hardness values are listed in Table 4, these having been made on both the Brinell and Rockwell machines, the "C" scale (diamond

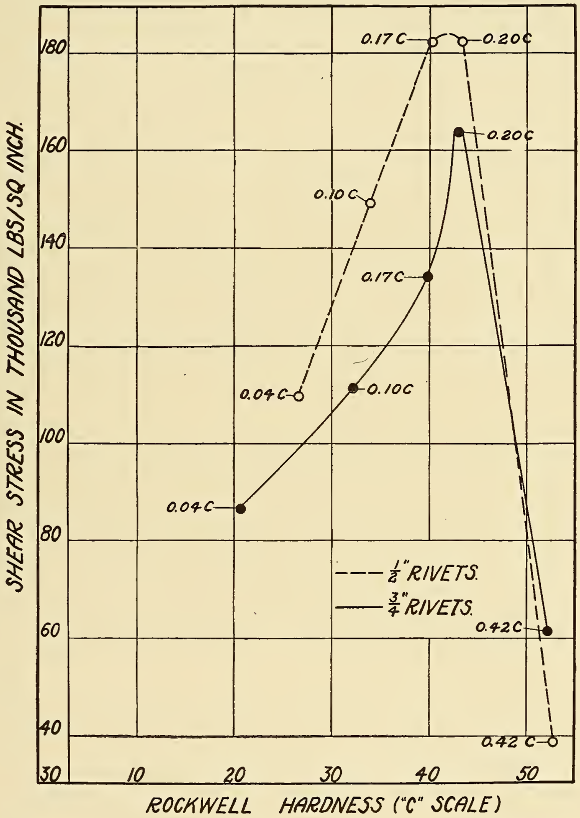


Fig. 8.—*Relation of Rockwell hardness to shear strength for rivets made of a 3.5 per cent nickel-1.5 per cent chromium steel*

point) being used on the latter. Figure 8 illustrates the relation of Rockwell hardness to shear strength for the steels of the 3.5 per cent nickel-1.5 per cent chromium series. The maximum strength was obtained with a Rockwell hardness lying between 40 and 45 ("C" scale), which for these steels corresponds to a Brinell of 375 to 450, as shown in Table 3. This hardness value corresponds rather closely to the hardness of light armor plate showing maximum ballistic resistance. Thus, steels finished as rivets possessing such hardness values should also possess high impact resistance.

TABLE 4.—*Brinell and Rockwell ("C" scale) hardness of rivets*

Specimen	½-inch rivets			¾-inch rivets			Remarks
	Brinell	Rockwell [1]		Brinell	Rockwell		
		Head	"Grip"		Head	"Grip"	
A	415	44		444	43.5		0.23 carbon.
B	514	49.5		495	48		0.28 carbon.
C	415	45		444	42.5		0.25 carbon.
D	477	49		471	51.5		0.35 carbon.
E	555	56		555	54		0.42 carbon.
54	262	27.5	26	223	21	22	0.04 carbon.
56	321	36	37	321	34	34.5	0.10 carbon.
57	422	44	44.5	402	43	43	0.20 carbon.
58	430	47	47	430	46.5	47	0.25 carbon.
68	388	40.5	42	369	39	40.5	0.17 carbon.
925	415	45.5					0.26 carbon. 1.00 manganese. 1.22 molybdenum.
926	331	45	46				0.25 carbon. 0.78 chromium. 0.81 molybdenum.
927	477	48.5	50.5				0.33 carbon. 0.62 chromium. 1.41 nickel. 0.49 molybdenum.

[1] Values given to nearest 0.5.

NOTE.—Hardness of "grip" was taken on portion of "grip" directly beneath head of rivet.

The structures of the steels illustrated in Figures 9, 10, 11, and 12 all show the angular needle form indicative of martensite. However, the hardness values clearly indicate that these steels are not fully martensitic. There is, however, some martensite present, as was shown by the expansion which took place in the rivets made up for tensile tests (this expansion being due to the increased volume resulting from the transformation of austenite to martensite). Furthermore, the dilatometric tests, the results of which will be described later, showed this volume increase to take place at temperatures closely approximating the Ar'', or martensite transformation in the thermal curves, also later described. This evidence definitely points to the presence of martensite in these steels. It is likely that it is present as a conglomerate mixture of martensite and ferrite and for lack of a better name will be referred to as "pseudo-martensite." It is hardly possible on the basis of the structures observed in these

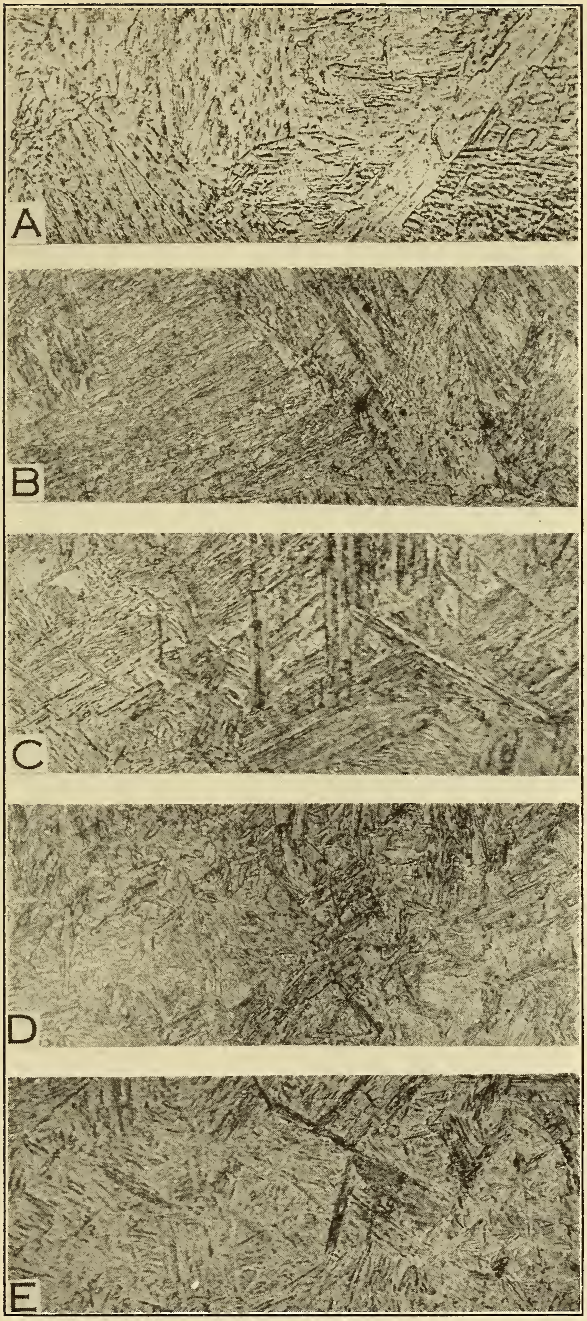


Fig. 9.—*Microstructure of the heads of ½-inch rivets. Etched in 2 per cent nitric acid in alcohol.* ×500

Reference	Carbon	Chromium	Nickel	Rockwell ("C" scale) hardness
	Per cent	*Per cent*	*Per cent*	
A	0. 23	1. 48	3. 83	44
B	. 28	2. 44	2. 40	49. 5
C	. 25	1. 54	4. 55	45
D	. 35	3. 67	2. 69	49
E	. 42	1. 35	3. 51	56

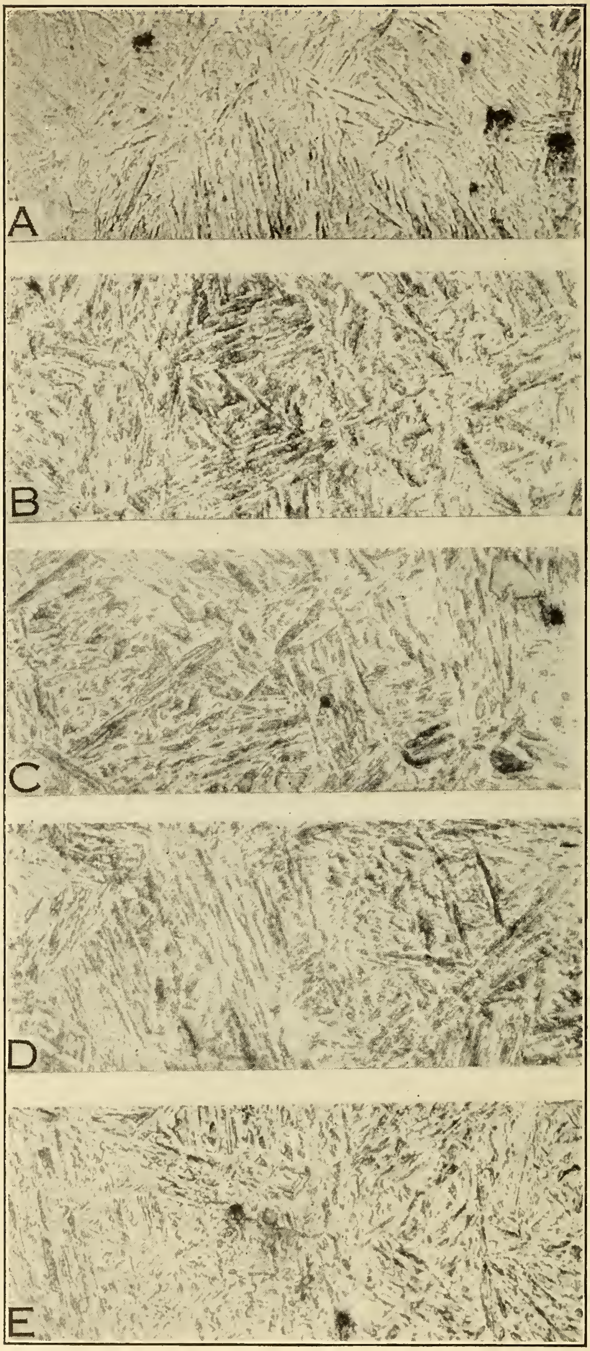


Fig. 10.—*Microstructure of the heads of ¾-inch rivets. Etched in 2 per cent nitric acid in alcohol.* ×500

Reference	Carbon	Chromium	Nickel	Rockwell ("C" scale) hardness
	Per cent	*Per cent*	*Per cent*	
A	0. 23	1. 48	3. 83	43. 5
B	. 28	2. 44	2. 40	48
C	. 25	1. 55	4. 55	42. 5
D	. 35	3. 67	2. 69	51. 5
E	. 42	1. 35	3. 51	54

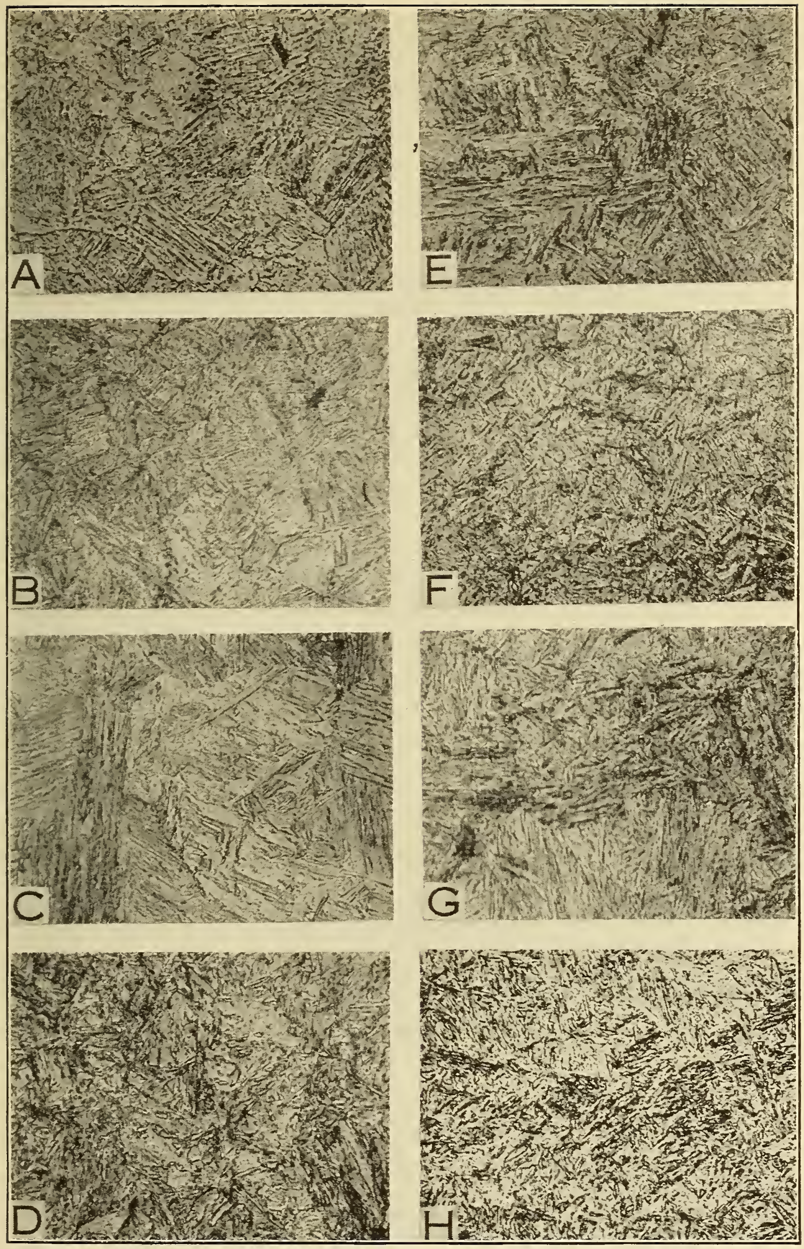


FIG. 11.—*Microstructure of the heads of ½-inch rivets. Etched in 2 per cent nitric acid in alcohol.* ×*500*

Reference	Carbon	Chromium	Nickel	Rockwell ("C" scale) hardness
	Per cent	*Per cent*	*Per cent*	
A	0.04	1.12	3.66	27
B	.10	1.82	3.31	36.5
C	.17	1.16	3.38	42
D	.20	.97	3.84	44.5
E	.25	1.48	1.84	47
F	.26		1.22 Mo 1.00 Mn	45.5
G	.25	.78	.81 Mo .82 Mn	45
H	.33	.62	1.41 .49 Mo .92 Mn	48.5

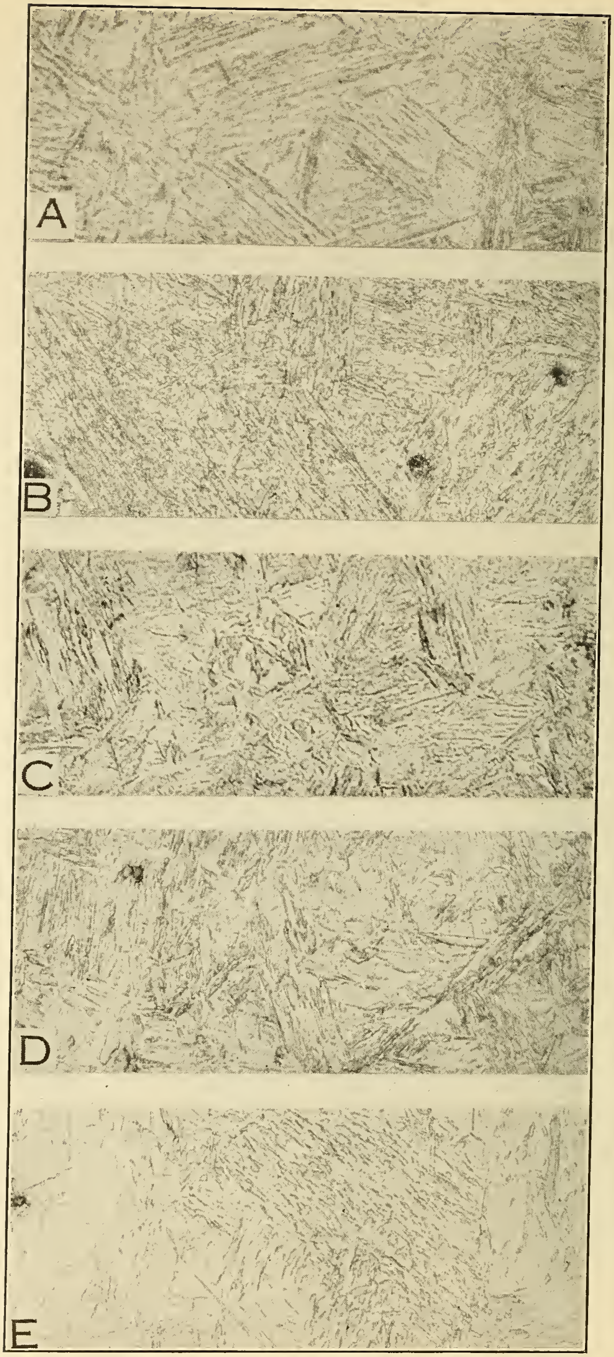


FIG. 12.—*Microstructure of the heads of ¾-inch rivets. Etched in 2 per cent nitric acid in alcohol.* ×500

Reference	Carbon	Chromium	Nickel	Rockwell ("C" scale) hardness
	Per cent	*Per cent*	*Per cent*	
A	0.04	1.12	3.66	22
B	.10	1.82	3.31	34.5
C	.17	1.16	3.38	40
D	.20	.97	3.84	43
E	.25	1.48	1.84	47

rivets, as shown in Figures 9, 10, 11, and 12, to determine which of the steels are superior. Figure 9, *E*, which is representative of the structure of steel E which contains a fairly high per cent of carbon, does, however, show a more clearly defined martensitic structure than the other steels. This steel, as shown in Figure 9, *E*, had a Rockwell hardness of 56 and a shear strength of only 37,000 lbs./in.^{2}, thus indicating that a well-defined martensite was too brittle and therefore undesirable in a rivet steel. On the other hand, a ¾-inch rivet of steel 54 (fig. 12, *A*), which showed a structure resembling sorbite and pearlite, also had a low shear strength. The balance of the steels were more or less similar in structure and possess high shear strengths. A "pseudo-martensitic" steel, therefore, appears to be the type of structure most desirable in a finished rivet.

VII. RESULTS AND DISCUSSIONS

The air-hardening property of the steels used was clearly demonstrated by the hardness values obtained, together with the high physical properties of these steels, as finished rivets. This was further verified by the microstructural features of these steels, as previously explained in this report, and by the cooling curves of several of the materials shown in Figure 13.

The temperatures of the heat absorption in the heating curves (fig. 13) correspond fairly closely to those of an alloy-free carbon steel, the influence of the chromium in raising the critical points being counterbalanced by the lowering effect of the nickel. A more important effect is shown in the decided lowering and partial suppression of the critical points in the cooling curves. The arrests at 440° C. (825° F.) (curve *A*), 315° C. (600° F.) (curve *B*), 390° C. (735° F.) (curve *C*), 285° C. (550° F.) (curve *D*), and 245° C. (470° F.) (curve *E*) indicate the martensite transformation referred to as Ar″, common to nickel-chromium steels of these types.

By noting the low temperatures at which the martensite transformation takes place it can readily be seen why the rivets appeared to "grow" in the joints as described under "tensile tests on finished rivets." Clearly, the temperature at the end of the transformation range was too low to allow shrinkage during cooling sufficient to counterbalance the expansion accompanying the transformation of austenite to martensite. This effect is diagrammatically indicated in Figure 14, which shows the results of dilatometric tests made on three of the steels. Curve *E* (fig. 14) obviously shows a greater total volume increase than curve *A*, because of the lower temperature at which the Ar″ takes place in the former (see fig. 13), thus giving less opportunity for the shrinkage effect following the transformation. The higher the position of the Ar″ in the cooling curve the longer the contraction range and the tighter should be the joint. Although the cooling rate of the rivet in the riveted joints and of the specimens tested in the dilatometer will not be the same, yet it is fair to conclude that steel A (curve *A*, fig. 14) will give the tightest joint of the three

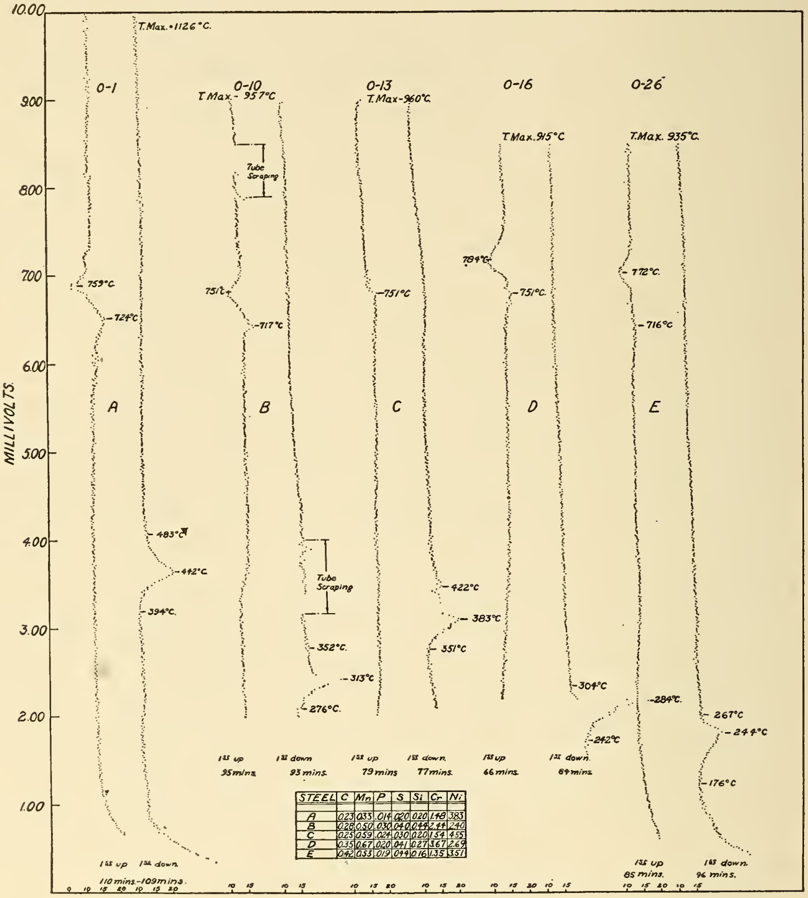


Fig. 13.—*Heating and cooling curves of some of the special rivet steels*

Steel	Composition						
	C	Mn	P	S	Si	Cr	Ni
A	0.23	0.33	0.014	0.020	0.20	1.48	3.83
B	.28	.50	.030	.040	.44	2.44	2.40
C	.25	.59	.024	.030	.20	1.54	4.55
D	.35	.67	.020	.041	.27	3.67	2.69
E	.42	.53	.019	.044	.16	1.35	3.51

steels represented in Figure 14. These tests indicated that a lower carbon content would be preferable from a standpoint of making a tighter joint, as the temperature of Ar″ would increase with decreased carbon.

Although there was no "tightening up" of the joints used for the tensile tests of finished rivets, due to rivet shrinkage, which might result in "head popping," yet a number of the rivets so tested broke at the head. (See Table 5.) This, however, was probably due to the square shoulder between the head and shank of the rivet. Such design is especially undesirable for steels of the chromium nickel series, as they readily develop fissures, and this coupled with a square shoulder may make such rivets readily subject to fracture. It would be desirable so to design the rivet holes as to produce a rounded shoulder in the finished rivet, as this would distribute the stresses rather than concentrate them, as is the case in the square-shouldered rivet. A carbon-steel rivet of the commonly used type which was tested in tension failed in the shank, the heads remaining intact, which demonstrates that a special design of rivet holes is probably not so essential for "plain" carbon steel rivets. The results of the tensile tests on finished rivets are given in Table 5.

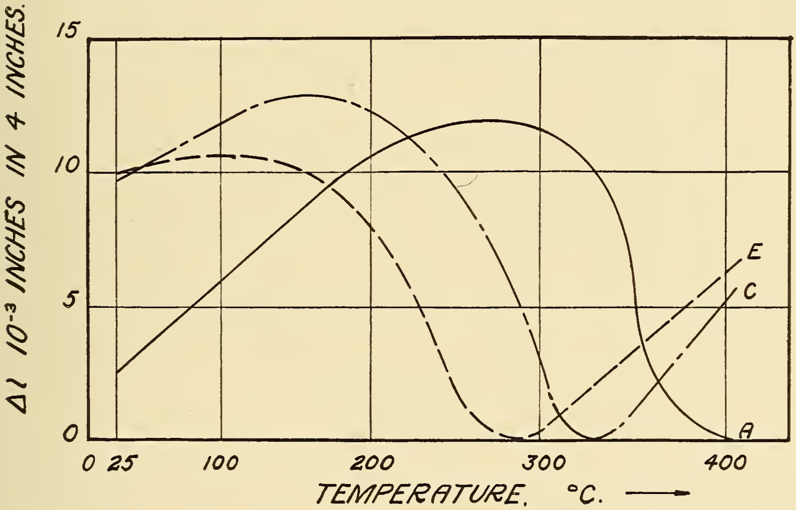


Fig. 14.—*Curves showing length changes which take place in a Ni-Cr steel during cooling through the martensite transformation (Ar'') down to atmospheric temperatures*

The results of the tensile tests, which were made on the standard 0.505-inch bars for the purpose of developing the difference in the effects of air cooling and cooling by contact with metal, are summarized in Table 6. A comparison of the results of Table 6 with the results of Table 5 for the one-half-inch rivets shows that greater strength was imparted to steels A, B, and C when cooled in contact with metal than when air cooled. However, a reversal of the effect of these cooling media was experienced with steels D and E. Steels D and E, because of their high-carbon content, are readily subject to internal stresses of appreciable magnitude when cooled rapidly.

These stresses are particularly localized in sections such as square shoulders of finished rivets. Square shouldered or notched conditions are not met in the standard tensile specimen, and it appears that this at least partially explains the superior tensile properties of the latter made of steels D and E. Steels D and E, although showing no elongation in the tests on 0.505-inch bars, showed about twice the strength of those as in the form of finished rivets.

Table 5.—*Tensile tests of finished rivets*

Specimen	Diameter of rivet	Maximum load	Maximum stress[1]	Ultimate load	Ultimate stress[1]	Remarks
	Inches	*Pounds*	*Lbs./in.*^{2}	*Pounds*	*Lbs./in.*^{2}	
A-1	¾	65,000	147,000	----------	----------	Broke in head.
2	¾	83,000	188,000	----------	----------	Do.
3	½	46,000	234,000	42,300	215,000	Broke in grip.
4	½	46,500	237,000	41,500	211,000	Do.
B-1	¾	52,500	119,000	38,600	87,500	Do.
2	¾	55,700	126,000	52,600	119,000	Broke in head.
3	½	38,600	196,500	----------	----------	Broke in grip.
4	½	52,600	268,000	----------	----------	Do.
C-1	¾	106,300	240,500	----------	----------	Broke in head.
2	¾	90,200	204,500	----------	----------	First 10,000 pounds applied rapidly; broke in head.
3	¾	99,500	225,000	----------	----------	Broke in head.
4	½	49,000	249,500	47,700	243,000	Broke in grip.
5	½	48,500	247,000	41,000	209,000	Do.
D-1	¾	48,700	110,000	----------	----------	Broke in head.
2	¾	61,200	138,500	----------	----------	Do.
3	½	17,400	88,500	----------	----------	Broke in grip.
4	½	15,000	76,000	----------	----------	Do.
E-1	¾	24,300	55,000	----------	----------	Broke in head.
2	¾	23,400	53,000	----------	----------	Do.
3	½	19,100	97,000	----------	----------	Do.
4	½	13,800	70,000	----------	----------	Broke in grip
F-1[2]	¾	25,300	57,000	17,500	39,500	
2	¾	25,400	57,500	17,700	40,000	
3	½	14,700	75,000	10,500	53,500	
4	½	14,000	71,000	10,900	55,500	

[1] Calculated on basis of cross section of rivet shank. The head actually comes into play, thus making these figures too high, and maximum loads are therefore probably the best figures for comparison.

[2] Comparison, regular rivet steel.

Table 6.—*Results of tensile tests on standard 0.505-inch bars*

Specimen	Diameter, original	Reduction of area	Elongation in 2-inch	Yield point[1]	Tensile strength	Appearance of fracture
		Per cent	*Per cent*	*Lbs./in.*^{2}	*Lbs./in.*^{2}	
A-1	0.506	12.6	10	168,500	200,000	Cup and cone; fine crystalline and silky.
2	.505	36.8	10	169,500	203,000	Cup and cone; silky.
B-1	.505	3.6	4	215.000	215,000	
2	.506	Nil.	1	196,000	196,000	Do.
C-1	.506	Nil.	0	162,500	162,500	Edge silky; balance dull crystalline.
2	.506	Nil.	0	181,500	181,500	Do.
D-1	.502	Nil.	0	155,500	155,500	Silky and crystalline; fan shape; flat surface.
2	.508	Nil.	0	146,000	146,000	Do.
E-1	.504	Nil.	0	150,000	150,000	Silky and crystalline; fan shape.
2	.506	Nil.	0	159,000	159,000	Flat, silky crystalline.

[1] Yield point was determined by noting the load at which a sudden break occurred in the stress-strain curve as appeared on an automatic stress-strain recorder with which the testing machine was equipped.

Stress-strain curves for steels A, B, and D in the air-cooled condition are shown in Figure 15 as being typical of alloy steels of this type. The proportional limit for these materials is in the neighborhood of 40,000 to 50,000 lbs./in.^{2}

Fissures present in many rivets of chromium-nickel steel may be brought to light by head-flattening and head-bending tests if such fissures are of any consequence. Only one type of specimen, the ½-inch rivet of steel E when tested for head flattening, failed under these tests. Figure 16 shows the type of failure produced in the head-flattening tests. Likewise, one specimen of steel E as shown in Figure 17 failed in the bend test.

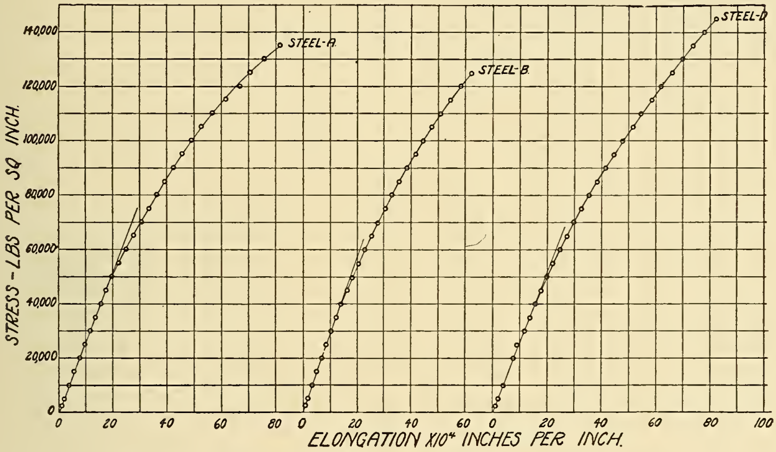


FIG. 15.—*Stress-strain curves of chromium-nickel steels*

[Average of 2 specimens]

Steel	Carbon	Chromium	Nickel
	Per cent	*Per cent*	*Per cent*
A	0.23	1.48	3.83
B	.28	2.44	2.40
D	.35	3.67	2.69

Discussion has thus far been restricted to the five steels originally selected for the determination of the applicability of air-hardening steels to rivet use. In the shear tests other steels were also used which contained lower percentages of carbon than were found in the original five steels. The results of the shear tests tabulated in Table 7 also include shear strengths for commonly used carbon and 3.5 per cent nickel steels. A comparison of these steels with the air-hardening steels shows the marked superiority of the latter. In general, the ½-inch rivets failed at higher stresses than the ¾-inch rivets, due to greater hardening of the former by virtue of their smaller mass and consequent higher cooling rate. This feature is illustrated in Figure 18, which also shows the relative shear strength of various compositions.

By referring to Figure 19, it can readily be seen how markedly the carbon content, other factors being constant, affects the physical properties of the steels. The optimum carbon content appears to be about 0.20 per cent for steels containing 3.5 per cent nickel and 1.5 per cent chromium. Not only did nickel-chromium steels containing about 0.20 per cent carbon show the highest shear strengths, but their fractures indicated that the rivets had some ductility, thus indicating at least a fair degree of toughness.

FIG. 16.—*Specimen after "head-flattening" test showing failure at edges*

Steel	Composition						
	C	Mn	P	S	Si	Cr	Ni
E	0.42	0.53	0.019	0.044	0.16	1.35	3.51

Of all the mechanical tests thus far discussed most attention should be paid to the shear tests, because these rivets approach nearest to the actual cooling conditions which would be met in a riveting job. It is desirable to have a steel applicable to all sizes of rivets, and a steel answering such specifications would obviously rate higher than one which is shown to be useful in one size only.

In Table 8 are listed the five steels described in Table 3 (first series) together with the results of various physical tests. Steels D and E are too brittle for rivet use and have relatively poor properties and can, therefore, be discarded in considering the steels of greatest promise. B has some promise for three-fourths-inch rivets, but not so much for the one-half-inch size. A and C appear to be very good in both sizes of rivets. Between the two, A would be the more desirable steel, as it contains less nickel than C and would, therefore, be cheaper to produce. Furthermore, A has slightly better mechanical properties than C.

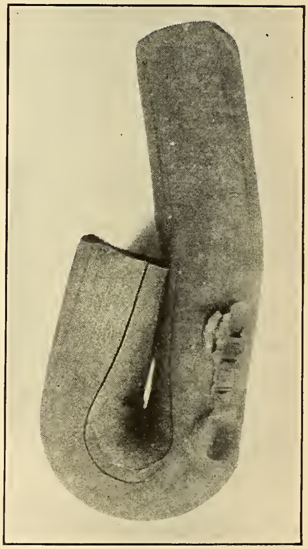


FIG. 17.—*Specimen after bend test showing failure*

Steel	Composition						
	C	Mn	P	S	Si	Cr	Ni
E	0.42	0.53	0.019	0.044	0.16	1.35	3.51

Steel 54 (Tables 4 and 7), although very tough, is too soft and hardly superior in strength to the commonly used 3.5 per cent nickel steel.

The approximate costs of the total alloying elements used in each of the steels listed in Table 3, computed on the basis of 1 ton of steel, are shown in Table 9. While the costs of chromium are calculated on the basis of low-carbon ferrochromium, it is possible in making the lower chromium steels—as, for example, steels 926 and 927, Table 3—to use the high-carbon ferrochromium without material increased difficulty in manufacture. The prices on low-carbon ferrochromium are twice those of the high-carbon product. However, these values should not necessarily be taken as the criterion in computing the differences in the costs of each steel, as the manufacturing difficulties met in the production of each must be considered.

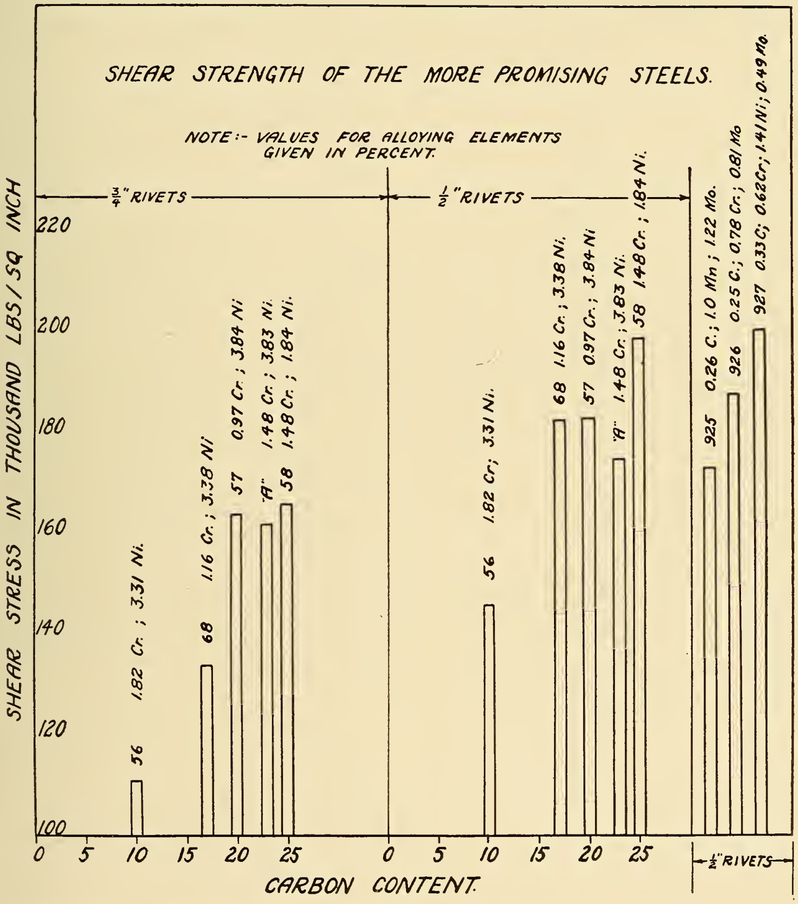


FIG. 18.—*Relation of shear strength to chemical composition for ½-inch and ¾-inch rivets*

TABLE 7.—*Results of shear tests*[1]

Specimen	Diameter of rivet shank	Actual failing load	Average of actual failing load [2]	Average failing stress [3]	Remarks
	Inches	*Pounds*	*Pounds*	*Lbs./in.*^{2}	
A-1	0.75	146,000	143,500	162,000	Breaks occurred in grip; very tough.
2	.75	141,000			
3	.5	66,000	68,500	175,000	One break occurred in grip; very tough.
4	.5	71,000			
B-1	.75	148,000	143,500	160,000	Broke in heads and grip; crystalline fracture.
2	.75	139,000			
3	.5	23,000	27,500	70,000	Very brittle; crystalline fracture.
4	.5	32,000			
C-1	.75	130,000	136,500	154,000	One head broke off and other break occurred in grip; very tough.
2	.75	143,000			
3	.5	63,000	65,500	168,000	Breaks occurred in head and grip; very tough.
4	.5	68,000			
D-1	.75	97,000	97,000	110,000	Broke in head and grip; rather brittle
2	.75	----------			
3	.5	65,000	68,500	175,000	Broke in head and grip; fairly tough
4	.5	72,000			
E-1	.75	64,000	54,000	61,000	Broke in head and grip; very brittle.
2	.75	44,000			
3	.5	14,000	14,500	37,000	Both heads broke and also broke in grip; very brittle.
4	.5	15,000			
54C	.75	76,500	77,000	87,000	Very tough; broke in grips.
54C	.75	77,000			
54B	.5	40,700	42,000	109,000	Tough; broke in head and grip.
54B	.5	43,500			
56F	.75	98,000	98,500	111,000	Very tough; broke in grip.
56F	.75	98,500			
56C	.5	58,500	57,500	147,000	Fairly tough; broke in grip.
56C	.5	56,500			
57B	.75	----------	----------	----------	Joint broke before rivet failed.
57B	.75	145,500	145,500	164,000	Fairly tough; broke in grip.
57A	.5	72,500	71,500	183,000	Tough; broke in grip.
57A	.5	70,500			Fairly tough; slight crystalline area; broke in grip.
58B	.75	148,000	147,000	166,000	Very tough; broke in grip.
58B	.75	146,500			
58A	.5	77,000	78,000	199,000	Tough; slight crystalline area; broke in grip.
58A	.5	79,000			Tough; slight crystalline area; broke in grip.
68A	.75	118,000	118,000	134,000	Fairly tough; broke in grip.
68A	.75	----------	----------	----------	Joint broke before rivet failed.
68C	.5	71,000	72,000	183,000	Fairly tough; broke in grip
68C	.5	72,500			
925	.5	65,500	67,000	173,000	Crystalline fracture; broke in head and grip; seam observed in fractured surface.
925	.5	68,500	----------	----------	Crystalline fracture; broke in head and grip.
926	.5	72,000	74,000	189,000	Crystalline fracture; broke in head and grip; seam observed in fractured surface.
926	.5	76,000	----------	----------	Fairly tough; broke in grip.
927	.5	78,500	78,500	201,000	Crystalline fracture; broke in head and grip.
927	.5	78,500			

[1] These tests were made on type of joint shown in Figure 1.

[2] Computed to nearest 500 pounds.

[3] Computed to nearest 1,000 pounds.

For comparison—	*Lbs./in.*^{2}
Common carbon rivet steel	35,000–45,000
3½ per cent nickel rivet steel	50,000–70,000

The balance of the nickel-chromium steels show good mechanical properties and may be considered for both ½ and ¾ inch rivets. Perhaps from an economic standpoint, steel 58 (see Tables 4 and 7) would be preferable to the other chromium nickel steels considered. It may, however, be desirable to reduce the carbon in this steel, and thus increase the toughness at the sacrifice of some hardness.

Nothing very definite can be said with reference to steels 925, 926, and 927, which contain molybdenum with other alloying elements, due to the few experiments made and the lack of ballistic tests. Nevertheless, the data which are made available by these few tests show promise for these steels.

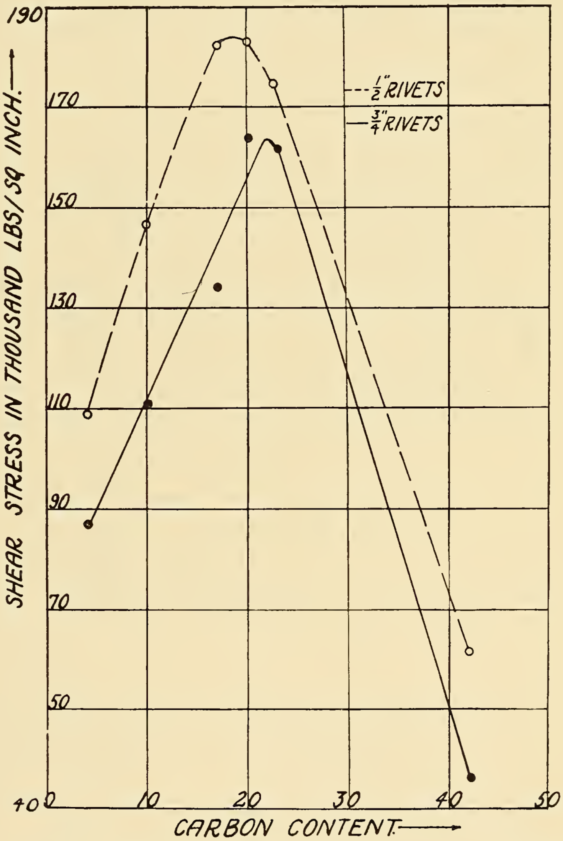


Fig. 19.—*Relation of carbon content to shear strength in 3.5 per cent nickel-1.5 per cent chromium steel*

The results of the ballistic tests are listed in Table 10 for the steels of the first series of Table 3. It will be noted that all ¾-inch rivets effectively resisted the 2,650 to 2,700 ft./sec. velocity ammunition and armor-piercing bullets without any injury of the holding power of the rivets. With the ½-inch rivets, steels A, B, and C gave good results, while D and E (E in 3 of 4 tests) failed by the heads snapping off on direct hits. This is in line with the brittleness previously found in these steels. Thus, it is again indicated that the higher-carbon steels are to be avoided. The order of the results of the tensile tests on finished rivets check the ballistic results rather well. No ballistic tests were made on the steels of the second series of Table 3. However, from shear strength and hardness it would be expected that A and C (Table 3, first series), 57, 68, 925, and 926 (Table 3, second series) would all act about alike in the ballistic test.

TABLE 8.—*Comparison of physical properties of five chromium-nickel steels*

[See chemical compositions, Table 2 (first series)]

Steel	Shear strengths of rivets 1½ inches long+heads			
	¾-inch rivets		½-inch rivets	
	Breaking stress	Remarks	Breaking stress	Remarks
	Lbs./in.^{2}		*Lbs./in.*^{2}	
A	162,000	Tough	175,000	Tough.
B	160,000	do	70,000	Fairly tough.
C	154,000	do	168,000	Tough.
D	110,000	Brittle	175,000	Very brittle.
E	61,000	Very brittle	37,000	Do.

Steel	Tensile strengths of rivets 3½ inches long+heads			
	¾-inch rivets, actual breaking load [1]	½-inch rivets		Remarks [2]
		Steel	Actual breaking load [1]	
	Pounds		*Pounds*	
C	98,500	C	49,000	Tough.
A	74,000	A	46,000	Do.
D	55,000	B	45,000	
B	54,000	E	16,500	
E	24,000	D	16,000	

Steel	Tensile strength of air-cooled 0.505-inch bars	
	Breaking stress	Remarks
	Lbs./in.^{2}	
B	205,500	Fairly tough.
A	201,500	Tough.
C	172,000	Brittle.
E	154,500	Do.
D	150,500	Do.

Steel	Hardness of rivets of shear test joints			
	¾-inch rivets		½-inch rivets	
	Brinell	Rockwell C	Brinell	Rockwell C
A	445	43½	415	44
B	495	48	415	49½
C	445	42½	415	45
D	470	51½	475	49
E	555	54	555	56

A and C have the same average hardness, or 430 Brinell (first).
D (second) 475 (average) Brinell.
B (third) 505 (average) Brinell.
E (highest) 555 (average) Brinell.

---

[1] Breaking load was not computed on unit basis due to a number of breaks occurring in the heads of the rivets, thus making computation of the area impracticable.

[2] Remarks apply to both second and fourth column.

TABLE 9.—*Approximate costs of total alloy per ton of steel used in each of the materials listed in Table 3*

Steel	Cost of total alloy [1] per ton of steel	Steel	Cost of total alloy [1] per ton of steel	Steel	Cost of total alloy [1] per ton of steel
58	$20.36	E	$31.50	A	$34.02
926	24.90	925	31.80	B	34.80
927	26.18	56	32.22	D	37.34
68	29.98	57	32.26	C	39.66
54	31.42				

[1] Chromium calculated on basis of low-carbon ferrochromium alloy.

TABLE 10.—*Results of ballistic tests on ½ and ¾ inch rivets conducted at Aberdeen Proving Grounds*

Rivet	Round	Remarks
A-1, ¾ inch	1	Hit near center and tore small pieces off edge; velocity, 2,618 ft./sec.
	2	Hit near center and tore small piece off edge slightly more than No. 1; velocity, 2,658 ft./sec.
	3	Hit about center and tore good-size piece off side; bullet penetrated about to surface of plate and glanced off; velocity, 2,737 ft./sec.
A-2, ¾ inch	1	Hit about midway between center and edge and tore small piece off edge.
	2	Hit about same as No. 1, on opposite side of rivet and produced same effect; velocity, 2,700 ft./sec.
	3	Hit same as No. 1 with same effect; velocity, 2,685 ft./sec.
	4	Hit fairly near center on top of No. 2 and tore a bit more off than other shots; velocity, 2,710 ft./sec.
		NOTE.—Rivet was relatively little affected.
B-1, ¾ inch	1	Hit side and knocked small piece off, but not very deep; velocity, 2,613 ft./sec.
	2	Hit same as No. 1 and slightly increased size of gap; velocity, 2,651 ft./sec.
	3	Hit other side in same manner as No. 1, and splashed part of edge off; velocity, 2,635 ft./sec.
	4	Hit center and splashed a little; velocity, 2,682 ft./sec.
B-2, ¾ inch	1	Hit edge and skimmed some of edge off; velocity, 2,651 ft./sec.
	2, 3, 4,	All hit edge same as No. 1.
	5	Hit center and splashed small amount.
C-1, ¾ inch	1	Hit midway between center and edge and splashed a little.
	2	Hit edge and grazed some of metal off.
	3	Hit same as No. 1 and sheared edge off.
CC-1, ¾ inch	1	Hit about the center and splashed small portion out.
D-1, ¾ inch	1	Grazed edge.
	2, 3	Hit near center; splashed some off head in each case.
D-2, ¾ inch	1	Hit near center and splashed small amount.
E-1, ¾ inch	1	Hit very close to edge and splashed very small piece off; velocity, 2,607 ft./sec.
	2	Hit in center; splashed small amount out; velocity, 2,620 ft./sec.
	3	Just grazed edge; very little or no effect; velocity, 2,650 ft./sec.
	4	Hit center and knocked small piece out; piece of bullet core stuck in rivet; velocity 2,650 ft./ sec.
E-2, ¾ inch	1	Hit edge; not much effect; splashed very small amount off edge; velocity, 2,664 ft./sec.
	2	Hit center and splashed a little.
A-1, ½ inch	1	Hit edge and splashed small piece off.
	2	Hit side and splashed small piece off.
	3	Hit directly in center and a small part of head remained.
A-2, ½ inch	1	Hit side and splashed small amount
	2	Hit center and broke off half of rivet head.
B-1, ½ inch	1	Hit side square and splashed small piece off.
	2	Hit edge with little effect.
	3	Grazed edge with no effect.
	4	Grazed off edge with little effect.
	5	Grazed side with no effect.
B-2, ½ inch	1	Hit squarely in center, splashed half of head off but did not affect "grip" of rivet at all.
C-1, ½ inch	1	Just grazed edge; no effect.
	2	Hit square in center and splashed half off.

TABLE 10.—*Results of ballistic tests on ½ and ¾ inch rivets conducted at Aberdeen Proving Grounds*—Continued

Rivet	Round	Remarks
C-2, ½ inch	1	Hit near center and splashed about one-fourth of head off.
D-1, ½ inch	1	Hit just at edge.
	2	Hit square on side and splashed head (exposed to fire) off; other head snapped off.
D-2, ½ inch	1	Along edge; just missing.
	2	Hit side and splashed piece off.
	3	About same as No. 2.
	4	Struck squarely midway between center and edge and drove "grip" of rivet back about ⅛ inch; three-fourths of rivet head splashed and rest snapped off.
E-1, ½ inch	1	Hit edge at angle, snapped head off, and drove rivet back about ¼ inch; head probably sheared off.
E-2, ½ inch	1	Hit side and glanced; splashed small piece out.
	2	Hit same as No. 1, on other side of head.
	3	Hit near center and only splashed small piece.
EE-1, ½ inch	1	Probably glanced on edge and snapped head off, including about ⅛ inch of "grip."
EE-2, ½ inch	1	Hit glancing blow on side and just skimmed surface off.
	2	Just missed front head but back head snapped off.
	3	Just grazed edge with very little effect.
	4	Snapped head off and about ¼ inch of grip went with head, probably hit rivet on edge.

NOTES.—

1. Where no velocity is reported, service bullets were used, which were found to have a velocity of 2,650 ft./sec. (approximately).
2. .30 caliber bullets were used throughout.
3. Four tests were made on ½ inch "E" type of rivet because of nonuniformity in results of E-1 and E-2.
4. Double letters as "EE" indicate rivet holes were countersunk before driving rivets.

VIII. SUMMARY

Experiments were conducted with a number of alloy steels having air-hardening properties with respect to their applicability as rivets. The principal conclusions to be drawn may be summarized as follows:

1. Air-hardening steels within certain limits are very satisfactory for rivets. With such steels riveted joints were produced under ordinary shop conditions which were four to five times as strong as those made with ordinary carbon steel rivets and more than twice as strong as those made with best (nonair-hardening) nickel rivet steels.

2. The regulation of the carbon in an alloy steel is very important, there being an optimum carbon content for each particular type of alloy steel. For a steel containing 3.5 per cent nickel and 1.5 per cent chromium the optimum carbon is very close to 0.20 per cent.

3. A drawback in the use of air-hardening steels for rivets is the loosening of "long shanked" rivets as a result of expansion caused by the change of austenite to martensite (Ar″) which takes place at relatively low temperatures. This difficulty, however, was not met in rivets of the lengths used in tanks, and it is believed that sufficient lowering of the carbon will avoid this trouble even in longer rivets. This may cause a decrease in strength, but this loss would tend to be counterbalanced by an increased toughness.

4. Having determined the optimum carbon content for steels with a content of 3.5 per cent nickel and 1.5 per cent chromium, the effect of varying that content so as to lower the cost of the steel was considered. Further, additions of manganese and molybdenum were made, the results showing great promise for the use of these alloys in rivet steels from the standpoint of both strength and economy.

5. Rivets which showed good mechanical properties and had Rockwell hardness ("C" scale) in the range of 40 to 50 showed excellent ballistic properties. The ballistic properties are a good measure of the impact resistance of a material. Hence, steels of the chromium-nickel series containing 0.17 to 0.25 per cent carbon should show high impact resistance, the maximum probably being reached by an 0.20 per cent carbon content.

6. The steels tested are listed according to cost of the total alloy content. The steels containing molybdenum were not as tough as the best of the nickel-chromium steels. However, improved toughness in the molybdenum steels can doubtless readily be obtained without too great a sacrifice of strength by a reduction of the carbon content.

WASHINGTON, June 18, 1927.

⁂