"T-1" Steel: A Proven Engineering Material

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"T-1" heat-treated alloy steel offers a yield strength approximately three times that of conventional structural carbon steel. At this high strength level, it has ductility and toughness suitable for all structual applications, and can be welded. Features of interest to structural engineers, including fabrication, welding, corrosion resistance, and column strength, are discussed. Examples of proven applications in heavy-duty equipment are given. The paper concludes with a brief history of alloy steels in bridge construction, and some suggestions regarding the use of "T-1" steel therein.

● THE TRUE WORTH of any alloy steel for engineering uses is its combination of desirable characteristics. For many years there have been available steels of very high strength, or of excellent weldability, or of superior toughness. Unfortunately, however, all of these, as well as other desirable properties, have never been combined in one steel. This paper, therefore, describes a constructional alloy steel to which the trademark "T-1" has been given, to demonstrate how this aim was accomplished.

Table 1 gives a typical chemical analysis of "T-1" steel. The carbon content is as low as or lower than that of conventional structural steels, to aid in welding. Beyond this, there are six alloying elements, each with a specific duty. Nickel, chromium and boron are used for deeper hardening, to help produce high mechanical properties in heavy sections; vanadium is added to resist heat-softening, and copper improves atmospheric corrosion resistance. Molybdenum plays a triple role: it promotes deep hardening, adds to high-temperature strength, and, with vanadium, resists tempering or heat-softening. Because this steel must always be quenched and tempered to produce the microstructure best suited to welding, molybdenum and vanadium permit the highest possible tempering temperatures to be used, with resultant benefit to toughness; their resistance to heat-softening prevents weakening in welded joints.

TABLE 1
TYPICAL CHEMICAL ANALYSIS OF "T-1" STEEL

Element	Composition, %
Carbon	0.15
Manganese	0.75
Phosphorus	0.026
Sulfur	0.030
Silicon	0.24
Nickel	0.85
Chromium	0.50
Molybdenum	0.45
Vanadium	0.05
Copper	0.31
Boron	0.0029

Table 2 shows the minimum tensile properties of "T-1" steel plates. It is re-emphasized that these properties are obtained by heat treatment (that is, by quenching and tempering by the mill or by the user), and that this steel should never be placed in final service in any other condition. It also should be noted that the minimum yield and tensile strength specification values are unchanged in plates up to 6 in. thick. For comparison, the minimum specified yield and tensile strengths of the two most popular ASTM bridge steels are shown. The yield strength of "T-1" steel is nearly three times that of ASTM A-7 steel and nearly twice that of ASTM A-242 steel, although the ductility limits of all three, as expressed by elongation, are very similar.

Figure 1 is a comparison of two stress-strain curves made on production heats — one for "T-1" steel and one for ASTM A-285, Grade C, which is a carbon pressure-vessel steel similar to ASTM A-7 structural steel but slightly lower in strength. The initial slope of the stress-strain curves, and thus the moduli of

TABLE 2
TENSILE PROPERTIES OF "T-1" STEEL COMPARED WITH ASTM A-7 AND A-242 STEELS

Plate Thickness, in.	Min. Yield Strength, psi	Tensile Strength, psi	Min. Elong. in 2 In., %	Min. Red. of Area, %
		(a) "T-1" Steel		
¼ to 2[1]	90,000	105/135,000	18	55[2]
2+ to 4[1]	90,000	105/135,000	17	50
4+ to 6[1]	90,000	105/135,000	16	45
		(b) ASTM A-7 Steel		
¾	33,000	60/72,000	21[3]	—
6	33,000	60/75,000	21.5	—
		(c) ASTM A-242 Steel		
¾	50,000	70,000[4]	18[3]	—
4	42,000	63,000[4]	23.5	—

[1] Inclusive. [2] 45 percent for ¾-in. thickness and less. [3] In 8 inches. [4] Minimum.

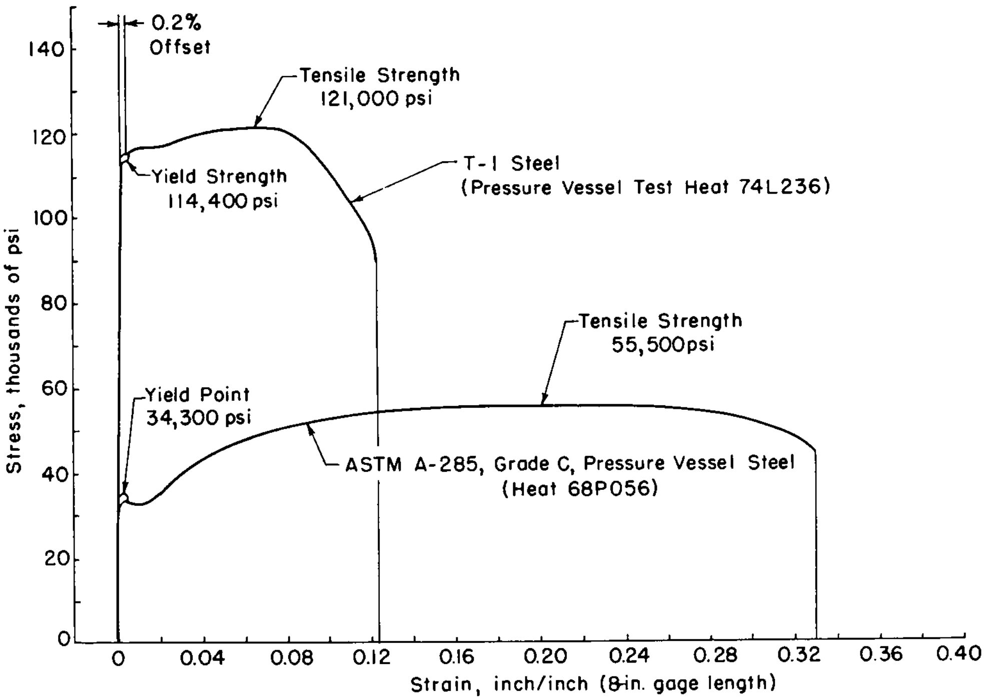

Figure 1. Typical tension stress-strain curves for "T-1" steel and A-288 steel.

elasticity, are the same for both steels. Next, assume an allowable stress of one-half of the specified minimum yield strength, and check to see what is left in each steel when this limit is exceeded. The allowable stress for ASTM A-285 Grade C (since its minimum yield point is 30,000 psi.) would thus be 15,000 psi., and the specimen shown in Figure 1 could take 19,300 psi. additional elastic stress before yielding. "T-1" steel, on the other hand, would have an allowable stress of 45,000 psi. Again referring to Figure 1, this specimen could take 69,400 psi. more, or over three and one-half times as much as the A-285 steel.

The high ratio of yield-to-tensile strength may disturb those who are accustomed to the low ratios obtained in carbon steels. Do not such high ratios, they ask, indicate poor ductility? That they do not is proven by hundreds of tensile tests which, at yield-tensile ratios of 90 percent or over, show elongation results well over the required minimum of 18 percent in two inches.

Thus, it appears that "T-1" steel has sufficient ductility to satisfy structural requirements. Next, should be considered the possibility that steel at such a high strength level and with such a high yield-tensile ratio, may lack toughness, which is the quality preventing brittle and catastrophic failure under either impact or static loading. It must be understood that, in most steels, this toughness is reduced as the steel gets colder; therefore, this characteristic of "T-1" steel should be examined.

The Charpy keyhole-notch test, which measures the energy needed to break a standard-size test bar containing a notch of established shape and size, is an accepted criterion of toughness. At room temperature, quenched and tempered "T-1" steel plates show Charpy keyhole impact values of 25 to 35 ft-lb, which is a satisfactory level of toughness. But room temperature conditions seldom prevail in nature, and engineers have learned to look critically at the behavior of many steels at sub-zero temperatures. Another criterion, but one well-established in pressure-vessel design, is therefore adopted. This requirement is that a steel should have a Charpy keyhole impact value of at least 15 ft-lb at its lowest operating temperature, to be considered tough.

The selected test is performed on "T-1" steel, dropping the test temperature successively lower in a search for the level at which the impact value drops to 15 ft-lb. This so-called "transition temperature" covers a wide range for most steels. For "T-1" steel plates up to 2 in. thick, the transition temperature lies between −150 and −255 F, or well below that of conventional structural carbon steels. Therefore, "T-1" steel is strong, ductile — and tough. But what happens in welding? Many people believe, with good reason, that welding a heat-treated steel will produce a soft, weakened zone. A very simple test proved that this was not true of "T-1" steel.

Two plates were joined with a butt-weld, a tension test specimen was machined therefrom, and the joint pulled apart. It cannot be too strongly emphasized that to weld "T-1" steel, either to itself or to anything else, low-hydrogen coated electrodes must always be used. Any abnormal introduction of hydrogen into the weld zone, either from cellulose coatings or from moisture in low-hydrogen coatings, will almost certainly result in underbead cracking. Table 3 shows the results of a series of tension tests on a transversely butt-welded specimen. When the strongest electrode was used (AWS-E-12015, 120,000-psi tensile strength) the test broke outside of the weld at 123,000 psi; thus, a joint efficiency of 100 percent was obtained. However, when an electrode of lower strength (AWS E-9015, 90,000-psi tensile strength) was used, the break sometimes occurred in the weld, giving a joint efficiency of about 94 percent.

The testing of electrodes at two strength levels was done because of a problem involving toughness of the weld metal. The AWS E-12015 electrode, as shown, provides 100 percent joint efficiency, together with plenty of ductility and a satisfactory level of toughness if the weldment is not stress-relieved. The

TABLE 3
TENSION TEST RESULTS ON TRANSVERSELY BUTT-WELDED "T-1" STEEL PLATES 1 IN. THICK

AWS Electrode Used	Condition	Ultimate Tensile Strength, psi	Location of Failure	Joint Efficiency, %
Base metal	As heat-treated	123,400	Base metal	100
E-12015	As welded	123,800	Base metal	100
E-12015	As welded	123,300	Base metal	100
E-9015	As welded	117,100	Weld metal	93.8
E-9015	Stress-relieved	113,900	Weld metal	91.4

weld metal deposited by nickel-molybdenum-vanadium electrodes of this type, however, is subject to embrittlement when it is exposed to the temperatures and times used in stress-relieving. But weld metal deposited by AWS E-9015 electrodes of the manganese-molybdenum type does not show this embrittlement and thus such welds may be stress-relieved without danger, but at the price of a less strong weld. At the time these experiments were carried out, these two types of electrodes were all that were available at the high strength level needed; since then, several companies have marketed electrodes for which it is claimed that 100 percent joint efficiency and retention of toughness after stress-relieving may both be attained.

However, except for very special cases, it is not believed necessary to stress-relieve a "T-1" steel weldment. It is generally true that welded joints, due to notch and heat effects, are less tough than the parent metal away from the joints. To find if this loss of toughness harmed "T-1" steel, a test known as the Kinzel test was used. A weld bead was laid on a "T-1" steel plate, a V-notch was machined in the bead, and the specimen was bent at room temperature. Other plates were bent at successively lower temperatures. The findings are not discussed in detail, save to say that the ductile-to-brittle transition of "T-1" steel by this test appears to lie between minus 40 F and minus 90 F, surely adequate for all atmospheric uses. This belief has been bolstered by results of a number of drop-weight and explosion-bulge tests made by the Naval Research Laboratory. Another practical test was performed to evaluate both the toughness and the response to stress-relieving of this steel, as follows.

A tank 4 ft in diameter and 20 ft long was built of welded ½-in. "T-1" steel plate. AWS E-12015 rod was used, and the tank was not stress-relieved. It was filled with calcium chloride brine at minus 50 F, and carried a 1-in. thick coat of frost when pressure-pumping was started. When the pressure had created a hoop stress of 90,000 psi., the theoretical "ballooning point," a 13-ton weight was dropped on the tank from a height of 52 ft. A lot of frost flew, but nothing else. The 13-ton weight was then dropped on the same spot from a height of 73 ft. This time the tank was dented, but the pressure held. Finally, a drop of 101 ft broke the tank into two pieces; but the break was ductile and there was no sign of brittleness. This test was repeated, using AWS E-9015 electrodes and stress-relieving, and the results were the same. This confirmed the belief that it is not generally necessary to stress-relieve a "T-1" steel weldment. The advantage this gives in field erection is obvious.

One might be pardoned for doubting that such a strong, tough material could permit the bending, shearing and machining incident to normal fabrication. But many thousands of tons of "T-1" steel have had these operations performed on them, and no problem is presented to a well-equipped shop. A quenched and tempered "T-1" plate can be gas-cut anywhere at any time, with no necessity for preheating or postheating. Welding may be done without preheating or postheating; in fact, it is preferable to avoid any excessive heat input, and to let the weld cool rapidly.

OTHER FACTORS

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TABLE 4

ATMOSPHERIC CORROSION TESTS OF "T-1" STEEL AND STRUCTURAL COPPER STEEL; EXPOSURE TIME, 3½ YEARS

Type of Atmosphere	Weight Loss, grams[1]	
	"T-1" Steel	Structural Copper Steel
Industrial	9.4	22.2
Marine	10.5	17.9
Rural	9.6	15.8

[1] Grams lost per 4-in. by 6-in. specimen.

sical properties of this new steel would be incomplete without mention of its corrosion resistance and its behavior in compression.

Table 4 presents the results of three and one-half years of exposure to three different types of atmospheres — industrial, marine, and rural. Under all three conditions the weight loss of "T-1" steel is about one-half that of copper-bearing structural steel, which itself is normally considered to have twice the atmospheric corrosion resistance of structural carbon steel. Thus, it can reasonably be expected that "T-1" steel will show much better resistance to atmospheric corrosion than will the standard grades of structural carbon steel.

Very little information is available on the behavior of columns made of very high strength steels. To obtain some information on the properties of "T-1" steel in compression, the United States Steel Corporation sponsored an investigation at Lehigh University. This investigation, although limited in scope, indicated that conventional column theory can be used to predict, within acceptable limits, the behavior of this steel in columns.

SOME APPLICATIONS

Out of current knowledge of the properties of this steel and out of the experiences of users, a few interesting applications may be mentioned.

The first use of "T-1" steel was in earthmoving equipment. It has been used for years in the buckets, bails, and dipper sticks of the giant 45-cu yd stripper shovels operating in the Midwest coal fields. Although its use was primarily aimed at weight reduction, its ability to take punishment has cut maintenance costs and down-time all along the line. Other applications have similar histories — bulldozer blades, moldboards and arms, dragline buckets, and truck and dump-car bodies and frames.

There are logical uses for "T-1" steel in static structures, as well. The first recorded use of alloy steel in the United States, for instance, was the chromium steel used by Eads in 1870 in a bridge over the Mississippi River at St. Louis. By the early 1900's, the 3¼ percent nickel steel was in use for high-strength members; it is now standard as ASTM A-8.

The search for a less expensive material led to structural silicon steel, which was used in building the hull of the steamer Mauretania in 1907, and which was later adopted by bridge builders. It was standardized as ASTM A-94 in 1925. However, this and similar steels depended on high carbon content, which was to prove very undesirable to the welders, who were beginning to appear on the scene. A gradual metallurgical development through the late 1920's and 1930's produced the high-strength, low-alloy steels which could be welded. Many of these conform to ASTM A-242, which is the present standard specification for low-alloy, high-strength structural steels. Thus, it is no radical departure to utilize high strength in static structures, and "T-1" alloy steel offers the highest strength level yet obtainable in a practical plate steel.

Its use can be justified, for instance, in monumental bridge structures, where a weight reduction at mid-span can effect considerable weight savings in load-carrying members throughout the structure, and in the supporting piers. Furthermore, its use to reduce the size of main load-carrying members will result in a reduction in the size, weight and cost of secondary members, which so often must be over-designed merely to match the size of main members. At least one large bridge has been designed using, in the "T-1" steel members, allowable stresses of about twice those normally used for high-strength, low-alloy steels such as ASTM A-242.

Bridge rockers are designed on the basis of yield strength. Here then, a definite premium is placed on the 90,000-psi yield strength of "T-1" steel. There are many other steels which can be treated to produce this yield strength level, but welding them is either difficult and expensive, or impossible.

And lastly, whether a bridge is painted every year or every twenty years, the superior corrosion resistance of this steel will give an extra margin of protection at the hidden rust spot that was missed on the last inspection.

In summary, it is pointed out that research and development are still intensive. Specialized data (including elevated-temperature strength, magnetic properties, temperature-dilation curves, etc.) have been gathered for specialized applications. Although the bulk of "T-1" steel production presently is in plates and bars, methods are being developed to make structural shapes, pipe, tubes, sheets and strip in "T-1" steel, a proven engineering material.