MATERIALS

STRENGTH OF STEEL AND THE PROBLEM OF ALLOYING

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> "Manganese, chrome, and titanium are all less harmful to steel, than calcium, silicon, magnesium, and aluminum."
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> P.P. Anosov, On Damascus Steels, in <u>Gornyy Zhurnal</u> (The Journal of Mining), Vol. 1, folio 2, 1841.

The widespread utilization of steel as construction material for the most responsible machine parts and other structures is attributable to the exceedingly advantageous combination of its mechanical properties, not inherent to other metals and alloys.

Steel is the most ancient metallic material familiar to mankind for several thousand years now. The qualitative characteristics of steel are first of all its ever increasing strength. A tensile strength of 300-350 kg/mm^2 in bulk samples and of 450-500 kg/mm^2 in wire was attained at the present time. Some 10-15 years back these figures seemed unattainable.

However these successes were achieved not through manufacture of new grades of steel or through optimal combining of the alloying components, but by producing a special structural condition.

On the Mechanical Properties. To produce high-test wares, one must strive to create a metal simultaneously manifesting a high resistance to plastic deformations (σ_b, σ_s) and high tensile strength (S_T). The former is necessary in the case of uniaxial stresses, the latter in the case of combined stresses.

In the process of extension, smooth samples submit to plastic deformation and the failure is caused by shearing. Consequently such tests, while characterizing the resistance of metal to plastic deformations, do not determine the resistance of metal to normal stresses, and, therefore, do not characterize the performance of metal in a state of complex stress (in machine parts with complex configuration). In sheeting there can be no state of multifold stress, and the tensile strength value, in this case, is essentially unimportant (if σ_s does not exceed S_T). If, however, a tube is to be manufactured from a sheet, then under the influence of internal pressure the stressed state will approach to that of compound stress, and the tensile strength value will assume a foremost importance, since failure, in this case, would occur without plastic deformation.

In the first approximation the practical importance of tensile strength may be estimated in the following manner. If on actual loading the object may be strained plastically to a considerable extent, then the indices of "tangential" strength (σ_s and σ_b) acquire a great importance. If the object, due to the peculiarity of the loaded state and other factors, fails to submit to plastic deformation, then predominant importance is to be attributed to the "normal" strength — tensile strength (S_T).

Thus, the more complex the shape of the part, the more complex is its state of stress, and the more important is the value of "normal" strength.

Notches and internal and external defects complicate the stress distribution and increase the share of normal stresses. The same influence is produced by the drop of temperature, increasing rate of load application, and other factors.

In developing a brand of steel or a heat-treatment process, it is impossible to envisage all the conditions of loading. It is, therefore, important to aim at producing the highest values of σ_s and S_T.

On the Determination of Brittle Strength. It should be noted that tensile tests of smooth samples do not reveal the normal strength, at any rate, not for so plastic a metal as steel. In determining the normal strength, the necessary conditions should be created to assure $\sigma \gg S_T$.

Objective data may be obtained in tensile tests of smooth samples at a very low temperature (at minus 253°C for high-quality steels).

Why is it that tensile tests conducted at liquid-hydrogen temperature determine the brittle strength at room temperature?

This may be explained by the fact that the breaking strength does not depend on the temperature, Figure 1, while the resistance to shearing stress increases rapidly with dropping temperature. This is why in establishing the ultimate strength of smooth samples at the temperature of liquid nitrogen, or even better, that of liquid hydrogen, we determine the breaking strength of the metal at the given or room temperatures.

However, it is very difficult to conduct tensile tests at such low temperatures, and it becomes necessary to resort to other methods of testing, which indicate only the qualitative regularities, for example, to impact tests. The high speed of testing and the notching of samples cause the share of normal stresses to be considerable here in the total complex of stresses. If the impact sample produces a tough fracture (this may be judged by the amount of impact energy and by the aspect of the fracture), then a given metal at a given stress, temperature, and rate of deformation exhibits a σ to S ratio such that rupture occurs as a result of tangential stresses. When a tough fracture is obtained, one of the factors should be so changed as to cause the share of normal stresses to increase. This may be achieved by increasing the impact rate, or by sharpening the notch, or, alternatively, by lowering the test temperature.

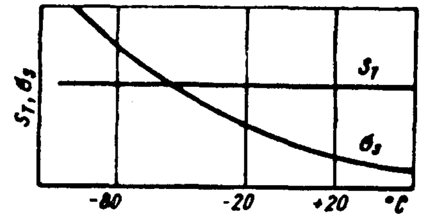

Fig. 1. Effect of the test temperature on the resistance to shearing stress and rupture (diagram).

Figure 2 shows the impact toughness of two types of steel in relation to the test temperature. They exhibit identical toughness at room temperature. However, the transition to a brittle state in steel A begins at minus 20°C, in steel B it starts at 80°C. This indicates that the value of "normal" strength is higher in steel B, and the temperature should be lowered still more for the yield point to exceed the "normal" strength. Steel B possesses a greater margin of toughness and a higher breaking strength. Since the lowering of temperature is equivalent to an increase in the rate of deformation, or the sharpening of the notch, a steel with a lower temperature of transition to brittle state is less sensitive to notching.

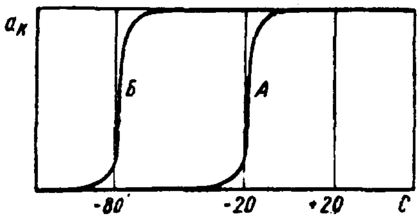

Fig. 2. Impact toughness of steels A and B versus test temperature.

Grouping of Steel According to Its Strength. Steels may be classified into groups characterized by the following ultimate tensile strength values.

Ultimate strength up to 70 kg/mm^2. Steels with σ_b = 50 to 70 kg/mm^2 in any composition and structural state possesses sufficient ductility to assure reliable performance. Such a strength is being achieved without heat treatment and in steels of simple composition.

Ultimate strength of 70-140 kg/mm^2 may be assured by various methods, but the best combination of mechanical and plastic properties is obtainable by tempering. The high ductility and toughness of thermally refined steels make their performace very reliable.

Ultimate strength of 140-180 kg/mm^2. At this strength level ductility and toughness appear to be considerably lower than at 70-140 kg/mm^2, but they are still maintained at a sufficiently high level (a_k = 4 to 6 kg/cm^2). Such strength values may be imparted to certain steels (for example 30KhGSN) by isothermal hardening.

Ultimate strength of 180-220 kg/mm^2. These values may be attained after regular heat treatment (hardening + low anneal) of alloyed steels containing about 0.5% C (which by their chemical composition approach to hot working steels). The ductility and toughness of these steels is low (a_k = 2 to 4 kg/cm^2), but in certain cases they may be utilized in the manufacture of machine parts.

Ultimate strength of 220-300 (350) kg/mm^2. These values may be registered in samples after thermo-mechanical treatment. The possible application of steel with such tensile strength to produce different wares has not yet been ascertained. It should be mentioned that ductility and toughness after this type of treatment are not lower than in the case of σ_b = 180 to 220 kg/mm^2.

Ultimate strength of 350-500 kg/mm^2. Such tensile strength was attained only for wire. The lower limit was registered for 1-2 mm dia. wire, the upper — for 0.1-mm wire, and then only in high-carbon steel after patenting and in a corresponding drawing process.

Ultimate strength of more than 500 kg/mm^2. This level of strength may be attained only in undislocated crystals. The fine size of the crystals (whiskers) makes it impossible to utilize such metals.

On Thermal Refinement. Modern science has at its disposal a vast quantity of experimental data on the properties of steels resulting from hardening and tempering (depending mainly on the drawing temperatures), and also after normalizing (depending on the composition of the steel and other factors).

Different steels may be distinguished by their behavior under varying tempering temperatures. In some steel the process of softening develops more rapidly, in others it is slower. Furthermore, the initial (martensitic) hardness and strength level is also different. Consequently, steels varying by composition after exposure to identical tempering conditions manifest different properties. This has given rise to the notion about the different mechanical properties of steel, about the more and the less sturdy steels, and so on. In reality this is not so. In comparing the properties of steel at the same level of hardness (it can be changed over a wide range solely by the tempering temperature), we see that at a given hardness all steels, regardless of the contents of carbon and alloying elements, have the same mechanical properties.

Recorded in Table 1 are the properties of the products of pearlitic transformation of austenite (different strength levels may be obtained by varying the temperature of decomposition and changing the contents of carbon and the alloying elements) and of the products resulting from the tempering of martensite. Table 1 shows the superior mechanical properties of tempered-martensite products at all strength levels and the appropriateness of the term "thermal refinement". Consequently, in order to produce the best possible complex of mechanical properties at the strength level of 70-140 kg/mm^2 hardening must be followed by tempering.

However, the properties assured by the products resulting from tempering of martensite may be obtained only in case of full refinement, i.e., with the entire cross-section manifesting the structure of tempered martensite. In the case of shallow refinement the mechanical properties deteriorate.

Mechanical Properties of Steel - TABLE 1

σ_b in kg/mm^2	$\sigma_{0.2}$ in kg/mm^2	δ_5 in %	ψ in %	a_k in kg/mm^2
After thermal refinement				
70	60	30	85	18—22
80	70	26	60	14—17
90	80	23	60	12—14
100	85	21	55	10—12
120	100	18	50	7—9
140	120	15	50	6—7
160	140	10	45	4—6
Thermally untreated				
50	35	30	55	10—15
60	40	22	40	8—12
70	45	18	30	5—10
80	50	14	22	3—6
90	55	10	18	2—4
100	60	6	15	1—2

Moreover, the mechanical properties may be reduced by structural defects (the brittle-phase network along the grain boundaries, large sonims, etc.). In the case of full refinement the mechanical properties may show values inferior to those listed in Table 1. This may be caused by superheating in hardening treatment, as well as by conditions responsible for the development of temper brittleness (drawing temperature, cooling, high contents of carbon, phosphorus, arsenic, and so on).

The theory of Critical Alloying. Thermal refining is the best method of assuring high mechanical properties. If the part is not fully hardened, thermal improvement will not impart to it sufficiently high mechanical properties. E.C. Bain's statement to the effect that the basic function of the alloying elements in structural steels is to increase hardenability is, therefore, fundamentally correct.

Indeed, in small cross-sections (for example, of 3 to 5 mm in diameter) of any steel, including carbon steel, it is possible to produce high mechanical properties, whereas in large sections, even if heavily alloyed, the mechanical properties fail to attain this level. At any rate, in case of full hardenability, high-alloy steels are not superior to low-alloy steels in terms of mechanical properties.

Consequently, the alloying elements do not improve the mechanical properties, but rather increase the hardenability of steels.

After the hardenability required for a given section has been attained, a further increase of alloying additions "excessive alloying" does not improve the mechanical properties, but rather heightens the threshold of cold shortness and reduces the margin of toughness, as it may, for instance, be seen from Table 2.

Thus, alloying to produce high mechanical properties must be minimal (critical) capable of assuring full hardenability required for a given cross-section and cooling conditions.

Consequently, if a steel contains a sufficient quantity of alloying elements to assure hardenability, then their further addition is harmful since this reduces the reserve of strength. The alloying elements by themselves do not improve the mechanical properties of steel, and the ostensible improvement on alloying is due to the influence the elements produce on hardenability, and not on the strength.

TABLE 2

Temperature of the transition to brittle* state (treated to σ_b = 100kg/mm^2).

Grade of Steel	Temperature of transition to brittle state in °C.
35KhR	—20÷—100
35KhGR	+40÷—40
35KhRT	+40÷—60
40KhN	—60÷—100
40KhNVR	—20÷—60
40KhGR	—20÷—60
40KhGVR	+20÷—40

*After the author's and O.N. Mesherinova's data.

The damaging effect of the elements in excessive alloying is varied. Chrome, manganese, boron, and titanium produce a negative influence, though, perhaps, to a lesser extent than aluminum and silicon. However, one element, apparently, presents an exception. Excessive alloying by nickel, judging by certain data, lowers the threshold of toughness. This explains the high toughness characteristics of nickel steels and the reason why nickel is so hard to replace as an alloying element for structural steels. The cause of the great influence produced by nickel has not yet been determined and was never made the subject of theoretical study.

Principles of Structural Steel Alloying. The content of carbon entirely determines the maximum strength value resulting after tempering at 200°C, and the minimum value after tempering at a temperature slightly below the critical point.

Excessive alloying, it seems, is less dangerous at low carbon contents than it is at 0.3 to 0.5% C (this postulate still requires checking). Impact toughness after refinement of low-carbon steels corresponds to the right-hand figures in Table 1, and for steels with average carbon contents to those in the left-hand column.

To assure the required hardenability the alloying elements may be introduced in any desired combination. It is recommended that use be made of the more rapidly available elements (manganese, chromium) and the strongly acting additions (boron, zirconium, and the rare-earth metals).

There may be a great number of possible combinations, yet one should bear in mind that the maximum values of the mechanical properties listed in Table 1 could not have been improved upon; the margin of toughness decreases as a result of excessive alloying. It follows, therefore, that parts with small and medium cross-section should not be made from high-alloy steels. If full hardenability may be assured through introduction of 1% Cr, preference should be given to steel 40Kh over the 40KhR and 40KhGR grades. Excessive alloying with nickel presents an exception.

High toughness and a low threshold of cold brittleness may be attained not only by means of refinement, but also through preservation of the fine austenite grain in the process of heating for hardening. For this purpose it is important to utilize hereditary fine-grained steels. A hereditary fine-grain structure may be developed by proper deoxidation of steel (1 kg of aluminum and 3-4 kg of titanium per ton of molten metal) to produce after solidification a steel with 0.01-0.02% Al and 0.03-0.05% Ti. The presence of aluminum and titanium in proportions higher than the above fails to refine the grain and lowers the toughness margin.

Additional light alloying of steel by niobium, vanadium, and zirconium (up to 0.05%) may, apparently, be useful to inhibit the grain growth. However, the use of these elements for alloying still calls for a practical verification. Tungsten increases only the hardenability, but its utilization is uneconomic because of its high cost.

Molybdenum eliminates reversible temper brittleness, which is very important for bulky objects in which temper brittleness cannot be removed by heat treatment. In such cases molybdenum is irreplaceable as an alloying element. Molybdenum also improves the hardenability of steel. For small-section parts, as well as for wares not subjected to high temper, additions of molybdenum to steel are, apparently, unnecessary.

We shall now briefly sum up the principles for the alloying of structural steels.

First of all the required hardenability must be assured by introducing into the steel the regular (chrome, manganese, nickel, and molybdenum) and the strongly acting (boron, zirconium, rare-earths) elements in avoiding excessive alloying. The cross-section of the part determines the appropriate selection of steel.

The hereditary fine-grained structure may be assured by corresponding deoxidation (Al+Ti) and retention of a very limited residual contents of these elements in the metal, and by possible additional microalloying (with V, Nb, or Ti).

A supplementary increase of the margin of toughness, as compared to that produced by thermal refinement and the fine austenite grain, may be assured through introduction of nickel (1-3%).

The development of temper brittleness may be checked by injecting 0.2-0.4% molybdenum.

A higher addition of molybdenum — owing to its strong effect on hardenability — may prove to be excessive and, therefore, undesirable.

NEW BOOKS

Bolokhovitnikov, N.F. Metallography and Heat Treatment. A university textbook. Fifth amplified and revised edition. Mashingz M, 1961, 464 pp., 30,000 copies. Price: 1 rub. 08 kop. in hard cover binding.

Theoretical principles of metallography: crystalline structure of metals, the theory of alloys, iron-carbon alloys, the doctrine of plastic deformation. The theory and the practice of heat treatment and cold work hardening, induction hardening and thermochemical treatment.

Vacancies and Other Point Defects in Metals and Alloys. Transl. from English by E.I. Estrin. Under the editorship of V.M. Rosenberg. Metallurgizdat, Moscow, 1961, 304 pp., 4300 copies. Price: 1.49 rub. in hard cover.

The influence of point defects on the mechanical properties of metals and ion crystals at low and high temperatures, on diffusion in them, their electric conductivity, density, and certain other properties. The formation of point defects in crystals.

For engineers-metallographers and laboratory technicians.

Grechin, V.P. The Wear-Resistant Cast Iron and Alloys. Mashgiz, Moscow, 1961, 128 pp., 5000 copies. Price: 40 kopecks.

The temperature of surface friction and the heat conductivity of materials employed in conditions of friction. The factors affecting the internal sliding friction coefficient. The mechanical properties and the wear of materials. The new brands of cast irons and alloys designed for work in conditions of friction at temperatures up to 800°C.

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For engineering and technical personnel.

NON-FERROUS METALS AND ALLOYS

ALLOYS OF THE Ti-Al-Mn SYSTEM

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The object of this work was to conduct a systematic investigation of the mechanical and technological characteristics of the alloys belonging to the Ti-Al-Mn system with the view to establishing the optimum alloy compositions for the manufacture of sheet material.

We have studied the alloys of the titanium group containing up to 9% aluminum and manganese. The alloys were sampled from the system's sections with the contents of titanium being constant and equal to 98.5, 97, 93, and 91%, Figure 1. These sections run through a large number of