quite low. Copper and nickel on the other hand have high elongation in the static test and relatively high notched bar impact properties.

The curves in Fig. 3 show the relation between notched bar impact properties and temperature. The values used for

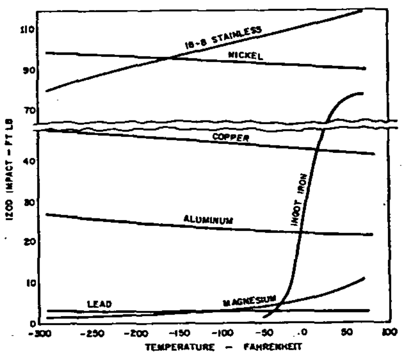


Fig. 3 .... Effect of Temperature on Izod Impact Properties of Several Metals[1]

determining the several curves were all not originally reported in the same units so that allowance must be made for some numerical accuracy although the trends are the same general order, no matter what type of notch is employed.

NONFERROUS ALLOYS

Except for 18-8 chromium-nickel stainless steel, only the pure metals have been considered up to this point in the discussion, but as alloys are used far more extensively in engineering structures than pure metals, alloys are of greatest interest.

There is very little information on the low temperature properties of zinc alloys. Indications are that zinc die casting alloys respond in a similar way to the pure metal as they suffer a loss in notch toughness with decrease in temperature. Because zinc is not a particularly tough metal by any standard of comparison, neither the pure metal nor its alloys are generally used for members that may be subjected to dynamic or bending stresses of any great magnitude.

The commercial copper-nickel, copper-silicon, copper-tin, copper-beryllium and copper-zinc alloys in general are not embrittled by low temperatures.

The commercial high nickel alloys such as nickel-copper, Monel and Inconel are not embrittled at temperatures as low as have been measured.

Lead alloys are seldom given much consideration for low temperature service. The embrittling temperature of the lead-tin solders is dependent upon the lead content. Solders containing over 70 percent lead are as tough at liquid air temperatures as at room temperatures but the 50-50 alloy embrittles at about −240 F. With higher tin ratios the embrittling temperatures are even higher, as pure tin embrittles at about −165 F. The leaded bronzes and brasses are not particularly tough at room temperature, but they retain about the same degree of toughness at sub-zero temperatures as at normal atmospheric temperatures.

Magnesium alloys usually become completely embrittled at temperatures below 0 F.

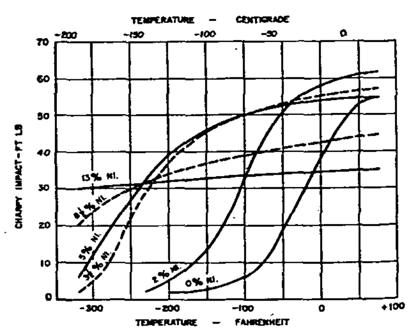
Aluminum, like copper, nickel and lead, improves in toughness with decrease in temperature, and most of the commercial aluminum alloys respond in the same manner. It should be noted, however, that in general the aluminum alloys which have highest strength properties have considerably lower ductility and resistance to impact than the pure metal.

STEELS

The low temperature properties of steel have been more thoroughly investigated than those of any other material as steel becomes embrittled at low temperatures, but the embrittling temperature is not constant as variations in composition and deoxidation practice have considerable effect.

When steel is in the as-rolled condition, or in a mildly heat treated condition such as normalized, annealed, or normalized and tempered, carbon increases low temperature embrittlement. Rimmed steels are poorer than semi-killed steels and fully killed steels are superior to semi-killed. Use of sufficient aluminum in deoxidation to insure a few hundredths of a percent of residual aluminum has proved of considerable benefit; consequently, steels for low temperature service are frequently specified to be made according to fine grain melting practice.

Nickel is recognized as the most effective alloying element for increasing resistance of steel to low temperature embrittlement. The temperature at which embrittlement occurs decreases with increase in nickel content up to about 15 percent nickel. With higher percentages of nickel, the impact properties of low carbon steels become practically non-



* All steels contain 0.01% carbon except No. 1020 (0.20%) and 2% nickel steel (0.15%).

Fig. 4 .... Effect of Nickel Content on the Resistance to Low Temperature Embrittlement of Normalized Low Carbon Steels (Keyhole Notch)*

varient at temperatures below atmospheric (Fig. 4). Manganese, within limits, is also beneficial in steel for increasing the resistance to embrittlement at low temperatures. Other alloys may exert a mild influence in improving the resistance of steel to low temperature embrittlement, but their effect is generally an indirect one of modifying the form and distribution of the carbides rather than a direct alloying effect on iron as occurs with nickel.

Condition of heat treatment has a marked effect. In the fully annealed condition, steels are in the poorest condition for resisting embrittlement, and although considerable improvement usually results from normalizing and further benefits are secured by a tempering or stress relieving treatment, best properties are obtained when the steel has been fully hardened, followed by tempering to moderate hardness levels. Even carbon steel, when fully hardened and tempered, possesses a considerable degree of toughness at liquid air temperatures despite the fact that the same steel may break brittle at temperatures above 0 F when tested in the as-rolled or in the normalized condition. It should be recognized, however, that with commercial quenching practices, carbon steels will not completely harden through in thickness greater than a few tenths of an inch, and the most frequently used alloy steels of the SAE or AISI types will not harden completely on quenching in oil if the section is greater than about one-inch in diameter.

TESTS

Even though the notched bar impact test has been the most widely used test for determining the suitability of metallic materials for low temperature service, the test has not received universal approval as the values are reported in energy units absorbed in breaking the specimen and cannot be applied quantitatively in design. Some question has been raised as to whether values obtained on notched specimens approximately 0.4 in. square reflect behavior of full size sections used in engineering structures. Also, considerable support has been given to the concept that the mode of propagation of fracture, i.e., shear or cleavage, is of greater importance than total energy to rupture. Another group advocates that the amount of plastic deformation be the criterion.

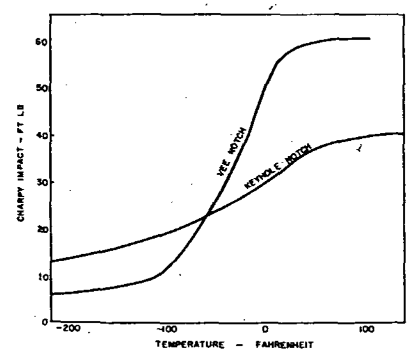
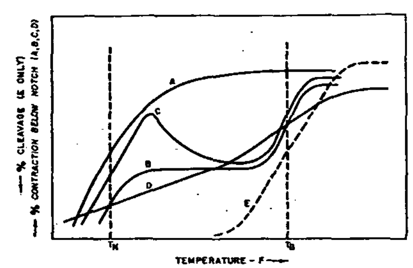


Fig. 5 .... Effect of Different Types of Notches on Impact Properties of a Normalized and Tempered Cast Nickel Steel

Most commercial specifications for material for low temperature service specify Charpy specimens with keyhole notch. This type of specimen is not quite as sensitive to small differences in properties as the Charpy bar with vee notch. Characteristic curves for the two types of notches are shown in Fig. 5.

There are a number of other types of notch tests that have been proposed for replacing the Charpy test such as the Kahn tear test, the Penn State slow notch bend test, the Lehigh slow notched bend test and modified form of a ballistic test.

Any of these tests can be used for determining the transition temperature of steels (the temperature distinguishing between



* Using Percent Contraction Below the Notch in Curves A, B, C, and D; Percent Cleavage in E.

Fig. 6 .... Diagram Showing Types of Transition Curves Obtained on Notched Specimens*

ductile and brittle behavior), but the transition temperature determined by any one test is not necessarily the same as that determined by another test method. In fact, the type of transition curve (Fig. 6) may change with the test method, and if the criterion is based on a condition of fracture common to all tests, such as 50 percent cleavage and 50 percent shear, transition temperature may vary as much as 50 F or more in the same steel when tested by different methods. It must be recognized that the temperature, the strain rate and the degree of restraint all affect the temperature of change from ductile to brittle behavior in any particular steel, and as these variables change with methods of test, it is not surprising that these differences in tranisition temperature are observed. Until a universally accepted test method is developed, the engineer can do little better than accept arbitrarily established limits that qualitatively indicate a level of toughness sufficient to meet service requirements. The ASME Boiler Construction Code for Unfired Pressure Vessels and the ASTM Specifications require that the steel must meet a minimum of 15 ft lb Charpy, keyhole notch, at the minimum service temperature.

SELECTION OF MATERIALS

There are problems connected with selection of material for low temperature service other than the low temperature