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Weld Metal Property Selection and Control

BY J. HEUSCHKEL

Guiding principles are provided to enable the welding engineer to select the necessary composition of steel weld metal to meet pre-specified mechanical properties

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ABSTRACT. When the American Welding Society was founded 52 years ago, under the leadership of Dr. Comfort A. Adams, the use of bare electrodes in air was representative of the state of the art for metal-arc welding. The resulting steel welds were porous and their strength, ductility, and toughness values were low.

Fabricators can now choose between at least six different shielded-arc processes. As-deposited steel welds may have tensile yield strengths between 38,000 and 207,000 psi, depending upon filler metal and process selection. Heat-treated welds may be even stronger. As-deposited tensile elongation values may range up to 50%, area reduction values up to 80%, and Charpy V-notch energy values up to 240 ft-lb. The multiple choices of filler metals, processes, and properties available challenge the designer and fabricator to select the technically most appropriate and the finally most economical filler metal-process-property combination for any specific weldment.

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Introduction

The as-deposited strength, ductility, and toughness of multipass ferritic and martensitic steel weld metals are primarily determined by their bulk compositions. Differing deposition techniques, for specific compositions, cause variations in the cooling rates, and consequently, in the weld hardness and grain sizes. Both of these factors alter the mechanical properties. Weld soundness is a fourth factor which influences mechanical properties. Porous deposits have significantly lower true tensile stress at fracture, tensile area reduction, and impact energy values, although the other mechanical properties are not particularly affected. Rate of application of strain is a fifth factor which influences the mechanical properties. Rapid strain rates tend to increase the elastic and plastic strengths and to reduce the ductility and energy absorption capabilities. Thus, while bulk composition, cooling rate, grain size, soundness, and strain rate all influence the mechanical properties, the most potent factor is that of composition.

Strengths increase when alloying elements are added to iron. The proportional limit, the yield strengths,

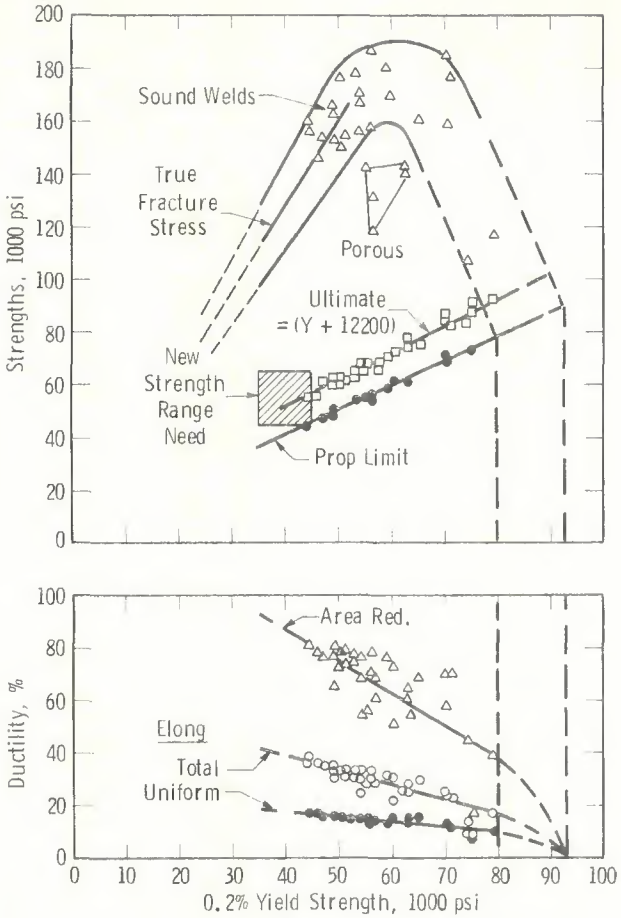

Fig. 1 — Tensile properties for unalloyed (Fe-Mn-Si-C) argon shielded metal-arc weld metals

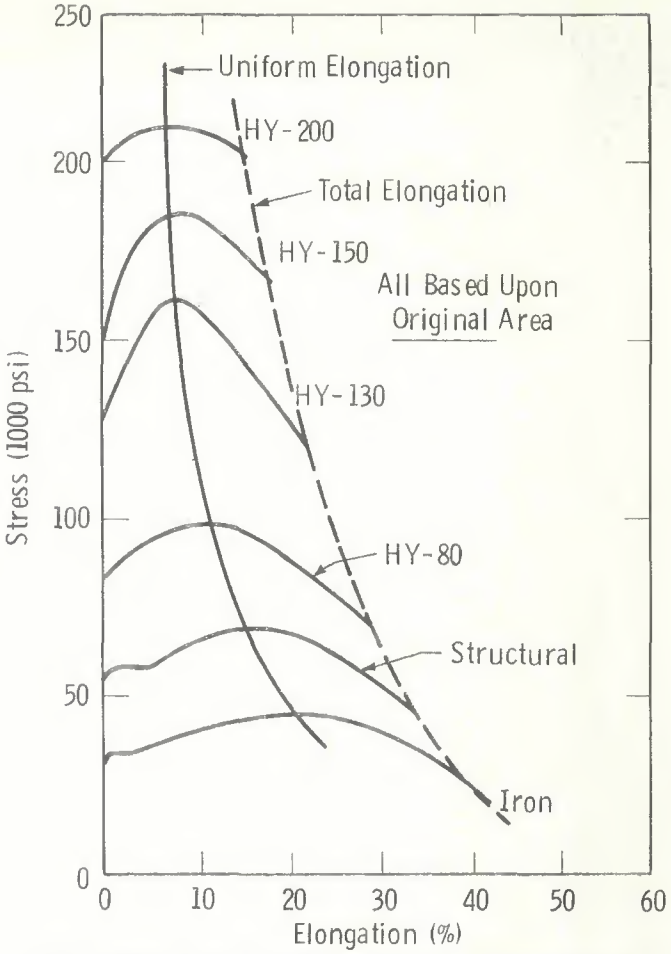

Fig. 2 — Stress-strain curves for weld metals of different strengths

and the ultimate strength tend to increase together.

For the first incremental alloy additions, the true tensile stress at fracture tends to increase more rapidly than any of the other strength indexes. As further alloying additions are made, the rate of increase of the true stress at fracture gradually decreases per unit of alloying element added. Still further alloy additions may reduce the rate of increase to zero. Further alloy additions, including carbon, manganese, and silicon, may result in a decrease in the magnitude of the true stress at fracture. This degradation can extend to the point where the true stress at fracture, even for carbon steels, becomes equal to the proportional limit stress. Fully brittle fracture occurs at that time, even in a smooth-bar tensile specimen — Fig. 1.

The differential between the true tensile stress at fracture and the tensile proportional limit stress largely determines the magnitude of the energy absorbed in the Charpy V-notch impact test. The apparent decline in the obtained impact energy values as the weld yield strength increases is really the consequence of the fact that the true stress at fracture does not continue to increase with increased proportional limit values for the higher alloy content, higher yield strength welds. The capability for obtaining further increases in weld toughness values, for the higher strength welds, therefore, lies in our ability to further raise the values of the true stress at fracture in the tensile test.

Specific explanations of the tensile and impact results obtained cannot be provided without knowing the mass composition of the individual welds. Most elements, when added to iron weld metals, increase their strength and decrease their impact energy values. The levels of C, Mn, P, S, Si, Cu, Ni, Cr, Mo, V, W, Co, Al, Cb, Ti, Zr, N, O, and other elements (As, Sb, Pb, Sn, Zn, B) are all important. The amounts of each element present in the weld deposit depend partially upon the process used.[1]

Oxygen detracts from weld toughness, and probably from weld strength. It is a leading candidate for minimization. Other elements, such as N, Mn, P, S, Si, Al, Cb, Ti, and Zr, rapidly degrade weld toughness, but at differing rates. Carbon, above some minimal level, rapidly degrades weld toughness. Higher levels of Cr, Mo, V, and W also degrade toughness.

The degradation of weld toughness with increased yield strength is a consequence of the fact that the alloying element additions commonly reduce toughness more rapidly than they increase strength. The optimum strength-toughness weld metal combination is obtained when the elements which detract from both the strength and toughness are minimized or eliminated, while the more potent strengthening elements are maximized.

The test welds provided tensile yield strengths from 37,500 to 207,000 psi and impact energy values from 2 to 240 ft-lb, both at room temperature. The impact fracture appearance transition temperatures (50% cleavage failure) ranged from more than +200 to less than -200 F.

The primary objective of this

Fig. 3 — Separation of 2 in. thick carbon steel plate during production welding

presentation, which summarizes research results obtained over the past 25 years, is to explain these wide ranges in mechanical properties, to show how the as-deposited-condition properties of steel welds are generated, how the several weld metal properties are interrelated, how properties should be selected, and how those properties may be controlled. Once that objective has been accomplished, the welding industry may better understand what composition ranges, and which welding processes, are most likely to provide the desired combination of mechanical properties in any particular case.

Test Procedures Employed

The described property-composition interrelationships are based upon tests of 443 individual multipass, as-deposited, steel welds made in 12 in. long and 1 in. deep grooves in 1¼ in. thick steel plates. These welds were crater-free. Any anomalies in the mechanical test results were caused by other factors. Transverse weaving of individual beads ranged from nil to two electrode diameters. Interpass temperature control was used so that the prior weld bead temperature did not exceed 250 F at the start of deposition of the subsequent bead. Normal heat inputs were used. All of the specimen layout, machining, mechanical testing, and chemical analyses were made in the same laboratories in the same manner by the same personnel.

Identified from the viewpoint of consumables, the processes involved were: bare metal-arc, manual; covered electrode, manual; cathode stabilized, argon-shielded, metal-arc, automatic; argon-oxygen shielded, metal-arc, automatic; helium-shielded, metal-arc, automatic; carbon-dioxide shielded, flux-cored, automatic; self-shielded, flux-cored, automatic; submerged, automatic; and both open shop and in-chamber, cold-wire-feed, argon-shielded, tungsten-arc, automatic. This more than covers the range commonly being used commercially, inasmuch as it included a series of 122 laboratory welds made in a sealed, evacuated, and purged chamber filled with dry, pure argon, an arc environment which assured minimum contamination by oxygen, nitrogen, and hydrogen.

Tensile tests were made at a constant strain rate of 750%/h on ASTM standard, 0.357 in. diameter, smooth-bar, longitudinal, all-weld-metal specimens, the axes of which were at the mid-width and mid-depth of the prewelded groove. A load-strain-to-rupture curve was recorded for every tensile specimen tested. Up to seven strength values and four ductility values were recorded for each tensile specimen. The strength values were: the proportional limit (stress at first 0.01% offset from linearity in the stress-strain curve), upper yield point (if one existed), lower yield point (if one existed), 0.2% offset yield strength, 0.5% offset yield strength, ultimate strength (maximum achieved load divided by original cross-section area), and true stress at fracture (final breaking load divided by final cross-section area). The ductility values were: yield point elongation (strain without increase in stress level at lower yield point), uniform elongation (strain at achievement of maximum resisted load), total elongation (strain in gage length at rupture), and area reduction at rupture.

The Charpy V-notch impact specimens were prepared with the long axes transverse to the weld, with the notch at the weld mid-width, and with the length of the notch extending through the depth of the weld. These tests were made in a 240 ft-lb capacity machine, often over the range from +200 to −200 F, and, in a few cases, to even lower temperatures. The energy of rupture, fracture appearance, and lateral expansion were observed for each specimen.

Anisotropy and Weldability

When selecting a weld metal for joining any particular steel, the weld metal and the plate metal strengths, ductilities, and toughnesses should be closely matched. Steel weld metal ductility indexes decrease as the strengths increase — Fig. 2. Steel components are seldom isotropic, that is, they do not have equal properties in the three directions. The lowest tensile true stress at fracture, tensile ductility, and impact energy absorption values for a steel plate are commonly in its through-thickness direction.[2] A steel so characterized is anisotropic.

When anisotropic steels are used in weldments subject to high orders of residual stress, and particularly when used with multiple-pass weld metals with yield strengths significantly above those of the base metal, the plate may fracture along planes of inclusions, as shown in Fig. 3. Such steels are high in planes of nonmetallic inclusion content discontinuities — Fig. 4. The microstructure may or may not be banded. The compositions of the inclusions, as determined by use of a microprobe, may consist of aluminum oxides, calcium silicates, manganese sulfides, titanium oxides, or other nonmetallic components — Fig. 5. Whether or not the inclusion composition has significance is questionable, except as a clue as to what should be eliminated from the steel.

The prewelded mechanical properties of the Fig. 3 piece of 2 in. thick, unalloyed carbon steel plate are listed in Table 1. The check analysis of this plate was: 0.26C, 0.78Mn, 0.004P,

Table 1 — Pre-Welded Mechanical Properties of Fig. 3 Steel Plate at +80 F

Tensile and impact property	Orientation			Ratio of through thickness to longitudinal value
	Longitudinal	Transverse	Through thickness	
Proportional limit, psi	41,900	38,900	44,100	1.05
Upper yield strength, psi	42,100	—	44,200	1.05
Lower yield strength, psi	40,100	—	42,900	1.07
0.2% yield strength, psi	40,900	38,900	43,000	1.05
0.5% yield strength, psi	40,200	39,700	45,100	1.12
Ultimate tensile strength, psi	74,800	75,000	61,400	0.82
Fracture, psi	141,500	133,800	65,300	0.46
Yield point elongation, %	0.76	0.35	0.30	0.39
Uniform elongation, %	18.80	18.63	3.30	0.18
Total elongation, %	32.87	32.28	3.52	0.11
Area reduction, %	58.70	54.60	7.42	0.13
Energy, ft-lb	29.2	27.4	9.1	0.31
Cleavage fract., %	79.0	69.0	90.0	1.14
Lateral expansion, in.	0.022	0.030	0.013	0.59

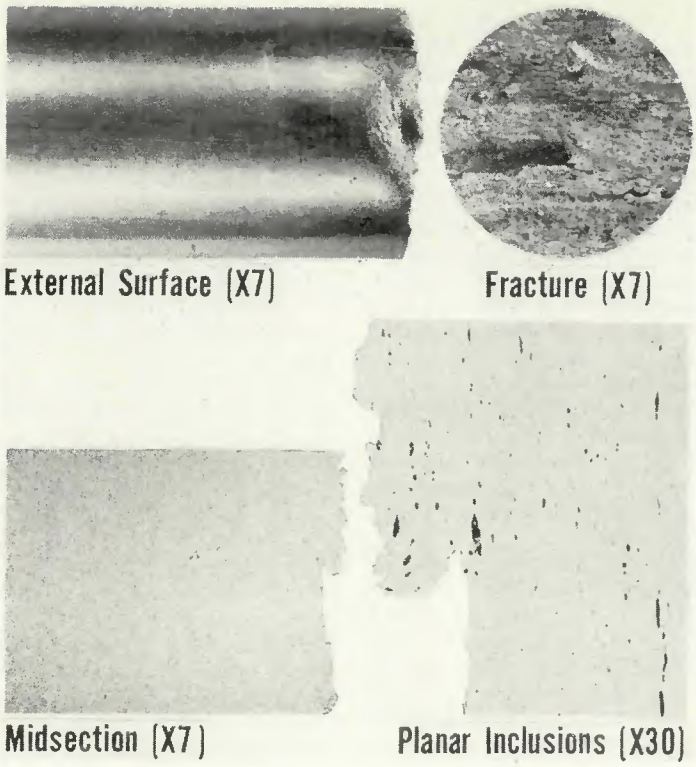

Fig. 4 — Fractured through-thickness tensile specimen from Fig. 3 plate stock. Views reduced 42%

0.028S, 0.25Si, 0.15Cu, 0.09Ni, 0.04Cr, 0.024Mo, 0.002V, 0.011Co, <0.001Ti, 0.0062As, 0.0023Sb, 0.0042Sn, 0.0038N, 0.0270 O, 0.004 Sol. Al, and 0.0008 Insol. Al_2O_3, by weight-percent.

When welding anisotropic steels, it is desirable that the yield strengths of the weld metals be maintained to a level equal to that of the base metal ±10%. With the unalloyed, anisotropic carbon steels, it is not practical to produce a weld deposit having a yield strength less than that of the 30,000 to 45,000 psi plate metal. The use of weld metals having yield strengths which approach such levels is feasible. At the opposite extreme, there is little technical or economic advantage in using an expensive high strength steel plate and then using a low yield strength weld metal to avoid plate splitting.

Strength, Toughness, and Composition Models

Tensile and impact data from the 443 as-deposited steel weld metal compositions tested provide the basis for the two models which describe their yield strength and toughness values — Fig. 6.

The first of these two models deals with yield strength. It proposes that pure iron, as the base for all of the weld metals being discussed, contributes a constant 37,500 psi to the tensile 0.2% yield strength of each weld, at room temperature, when loaded at a constant strain rate of 750%/h — Fig. 7. All strength increases above that level are considered to be the consequence of the addition of one or more alloying elements, individually or in combination.

Continuous unlimited increases in yield strength cannot be obtained by simply adding more and more alloying elements. For example, additions of chromium first tend to increase and then to decrease the yield strength, whereas yet further increases in chromium content have little influence upon that property. Aluminum additions to carbon steel weld metals follow a similar pattern, but at different levels of the element added. Excessive additions of other alloying elements tend to decrease the yield strength. The additions of an individual alloying element to iron, or to the alloy matrix, may first increase the yield strength linearly, in direct proportion to those additions, or in a more or less rapid manner. The Fig. 6 model, along with appropriate mathematical expressions, provides the means for defining the optimum compositions for particular strength levels.

The proposed Fig. 6 composition-toughness model accepts the fact that there is no increase in the absorbed impact energy above the 240 ft-lb level, the capacity of the testing machine used. Additions of an element, or combinations of elements, to iron may either have no influence upon the 240 ft-lb impact energy values, or they may decrease those values. The latter case is the usual one. Carbon is an example. For one group of welds, carbon levels up to about 0.14% could be used without impact energy degradation, whereas in another group, carbon levels above 0.054% caused rapid decreases in impact energy absorption capabilities. In both instances, further additions of carbon decreased the energy absorbed as a power function of increased carbon content.

Further details of both models are described in a later section.

Tensile Properties of Welds

Iron

Iron welds exhibit low strengths, high ductilities, and high impact energy absorption capabilities at room temperature. The tensile properties of argon-shielded, consumable electrode iron weld metals, when loaded in tension at a constant strain rate of 750% per hour, are shown in the left view of Fig. 7. The true stress at fracture was 142,250 psi — that is, 3.81 times that of the 37,300 psi proportional limit stress.

Individual additions of pure elements to pure iron add little to its strength. This has been demonstrated for both wrought steel plates[3-10] and as-deposited weld metals.[11] Ferrite grain size has a pronounced effect upon yield strength; the coarser the grain, the lower the strength, and vice versa.[11] Binary alloy weld metal yield strengths of 15,000 to 33,300 psi were obtained at room temperature, when loaded at a strain rate of 0.006 ipm (36%/h).[11] The published data demonstrate the need for more complex alloys, when higher strengths are required.

Unalloyed Carbon Steels

Bare, Metal-Arc. Unalloyed weld metals, deposited with the manual, bare, metal-arc process, had a yield point tensile strength of about 43,000 psi, an ultimate strength of about 57,000 psi, and a total elongation of about 6%.[12-14] Such weld metals, made and tested with present-day procedures, provide similar results at room temperature (Fig. 8): 47,600 psi proportional limit; 48,500 psi, 0.2% yield strength; 62,800 psi ultimate; 73,800 psi true stress at fracture; 9.3% elongation; and 23.3% area reduction.

The elastic tensile values increase as temperatures decrease below ambient in the manner characteristic of body-centered-cubic metals,[15] down to the temperature (about -80 F) where failure in the smooth-bar

specimen is limited by the true stress at fracture — Fig. 8. As the temperatures increase above ambient, the proportional limit gradually decreases. Between room temperature and +500 F, there is almost no change in the 0.2% offset yield strength, but above +600 F, the yield strength decreases rapidly.

A minimum in nominal ultimate tensile strength first occurs at +200 F — Fig. 8. Above +200 F, the ultimate strength increases, although between +290 and +490 F, failure occurs on rising load, being limited within that range by the true stress at fracture value. Above +490 F, the ultimate strength again decreases with increases in temperature.

Tensile elongation values are a maximum at 0 F, and again above +500 F — Fig. 8. There are two distinct brittle ranges: below -80 F and between +200 and +500 F.

The welds were commonly porous as a result of the carbon-oxygen reactions, and the temperature variable solubility of nitrogen in iron.[16,17]

This test weld contained 0.03C, 0.18Mn, 0.04Si, 0.14N, and 0.15%O. The yield strength value fits the Fig. 6 strength model when nitrogen is considered as a strengthening element and oxygen as an almost equally effective strength detractor.

Covered Electrodes. The 1950 state of the art for unalloyed carbon steel covered electrode welds is summarized in Fig. 9. The several tensile properties are shown as response variables to the weld metal 0.2% yield strength, "Y," which varied over a 47,800 to 65,800 psi range. The average proportional limit was Y + 5000 psi. The ultimate strength, "U," increased linearly with yield strength. It may be expressed as U = Y + 10,900 psi. The true stress at fracture increased linearly with the yield strength; the ratios were 2.5:1 for sound welds, and 1.75:1 for welds containing porosity. The highest individual true stress at fracture value was 185,200 psi.

The tensile ductility values generally decreased as the yield strengths increased — Fig. 9. There was minimum scatter among the uniform elongation values, the slope of the yield strength-uniform elongation curve was negative, and the average strain at occurrence of maximum load was 16%. The scatter among the values for total elongation was larger, the slope of the yield strength vs. total elongation trend curve was negative, and the average obtained total elongation value was 26.8%. The scatter among the area reduction values was much greater, the general slope of the yield strength vs. area reduction trend was negative, and the average of the obtained area reduction values was 55.1%.

The composition ranges for these welds were: 0.05-0.10C, 0.25-0.78Mn, 0.008-0.015P, 0.010-0.030S, 0.06-0.60Si, 0.006-0.043N, and 0.033-0.110%O, by weight.

These observations conform to earlier published results.[18]

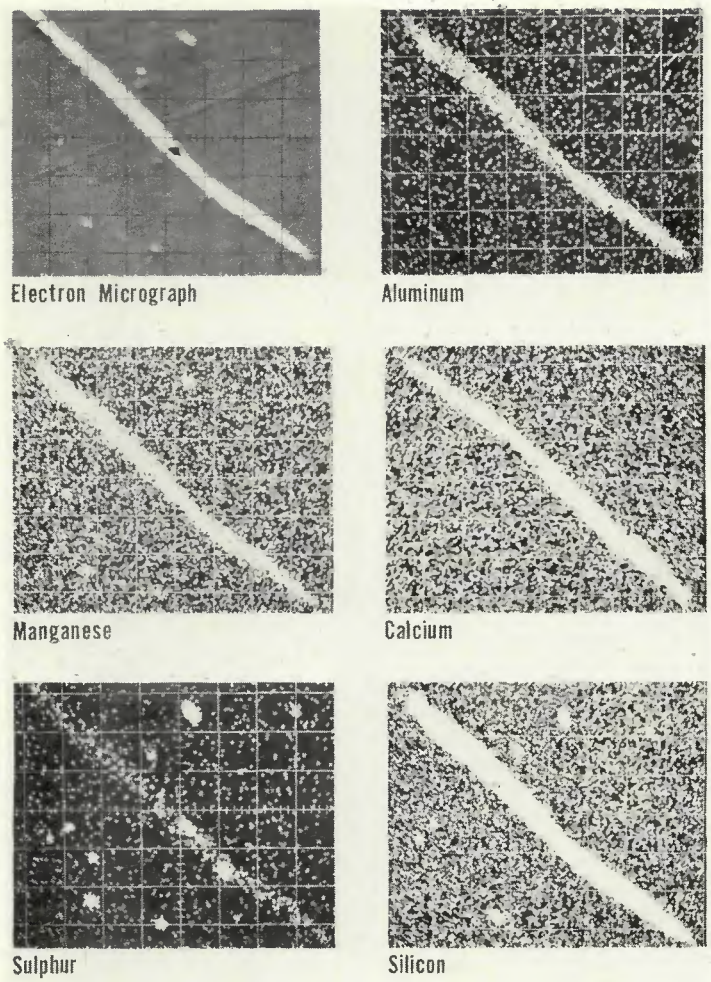

Fig. 5 — Microprobe revelations of plate inclusion compositions (X575 reduced 42%)

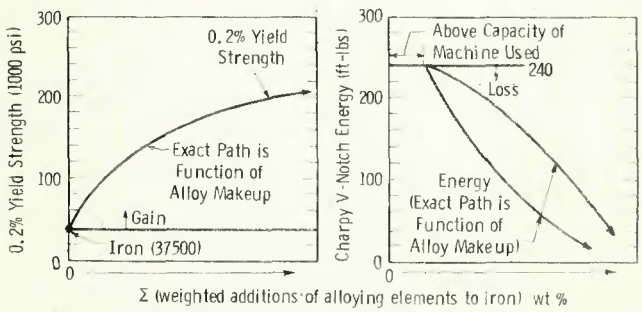

Fig. 6 — Models depicting weld metal strength and toughness responses to changes in composition

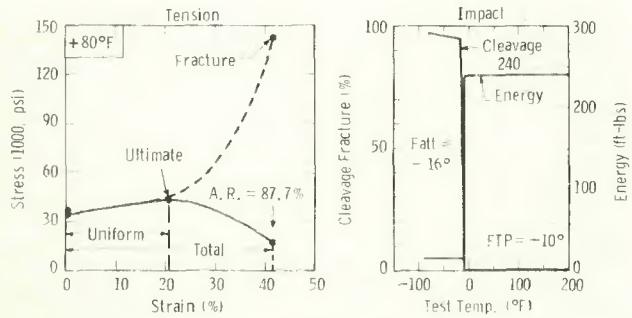

Fig. 7 — Tension and impact values for nominally pure iron weld metals (argon shielded metal-arc)

Argon-Oxygen Shielded, Metal-Arc. Some of the electrodes used in this series of experiments were copper coated. Eight of the welds made from such electrodes contained from 0.15 to 0.86% copper, by weight. The weld deposit compositions ranged from 0.081-0.19C, 0.52-1.58Mn, 0.32-0.94Si, and 0.0045-0.093%N. Both 2 and 5% oxygen contents were used in the argon shielding gas. As a result, the oxygen contents of the weld deposits varied from 0.013 to 0.044%. The phosphorus, sulfur, and nickel contents were all low, being less than 0.017, 0.024, and 0.06%, respectively.

The tensile results from a 1965 series of 21 welds, which included both experimental and commercial compositions, are shown in Fig. 10. The proportional limit and ultimate strength values increased uniformly with increased 0.2% yield strength. The true stress at fracture values, like the area reduction values upon which they are partially based, exhibited wide scatter bands. For the sound welds, the average ratio of true stress at fracture to yield strength was 2.56:1, whereas for the welds containing porosity that ratio was 1.73:1.

As the 0.2% yield strength increased above 63,500 psi, all of the ductility indexes progressively decreased. There was little scatter in the uniform elongation values, considerable scatter among the total elongation values, and extensive scatter among the area reduction values — Fig. 10.

Surface Cathode Stabilized, Argon-Shielded, Metal-Arc. A 1953 series of 34 welds, each from a laboratory melted heat of differing composition, was made with a system involving the use of a solid electrode having a light surface addition of metallic oxides: CaO, MnO, and TiO_2. This combination of materials was applied to the electrode surface after drawing to final diameter to stabilize the argon-shielded cathode so that the arc could be operated under straight polarity conditions.[19,20]

The weld metal compositions ranged from 0.019-0.25C, 0.49-1.96Mn, 0.02-1.01Si, 0.003-0.018N, and 0.014-0.030%O.

The tensile data are summarized in Fig. 1. The proportional limit and ultimate tensile strengths increased uniformly and linearly, with little scatter, as the 0.2% yield strength increased from 44,375 to 79,800 psi. The true stress at fracture increased with the 0.2% yield strength value at a ratio of 3.2:1, up to a yield strength level of about 55,000 psi. A maximum true stress at fracture value of 186,000 psi was achieved at about 57,000 psi yield strength. At this strength level, the differential between true stress at fracture and the proportional limit was 130,000 psi. For the welds having 0.2% yield strengths above 65,000 psi, the true stress at fracture deteriorated to the extent that, by projection, it equalled the proportional limit within the yield strength range from 80,000 to 93,000 psi — Fig. 1. This is the condition necessary for brittle fracture in a smooth-bar tensile specimen. While the tests were not extended to that extreme, some of the stronger welds approached the nil ductility level.

The highest carbon content weld (0.25%C) had a total elongation of only 6.8%, and an area reduction of 9.1%. Maximum scatter was ob-

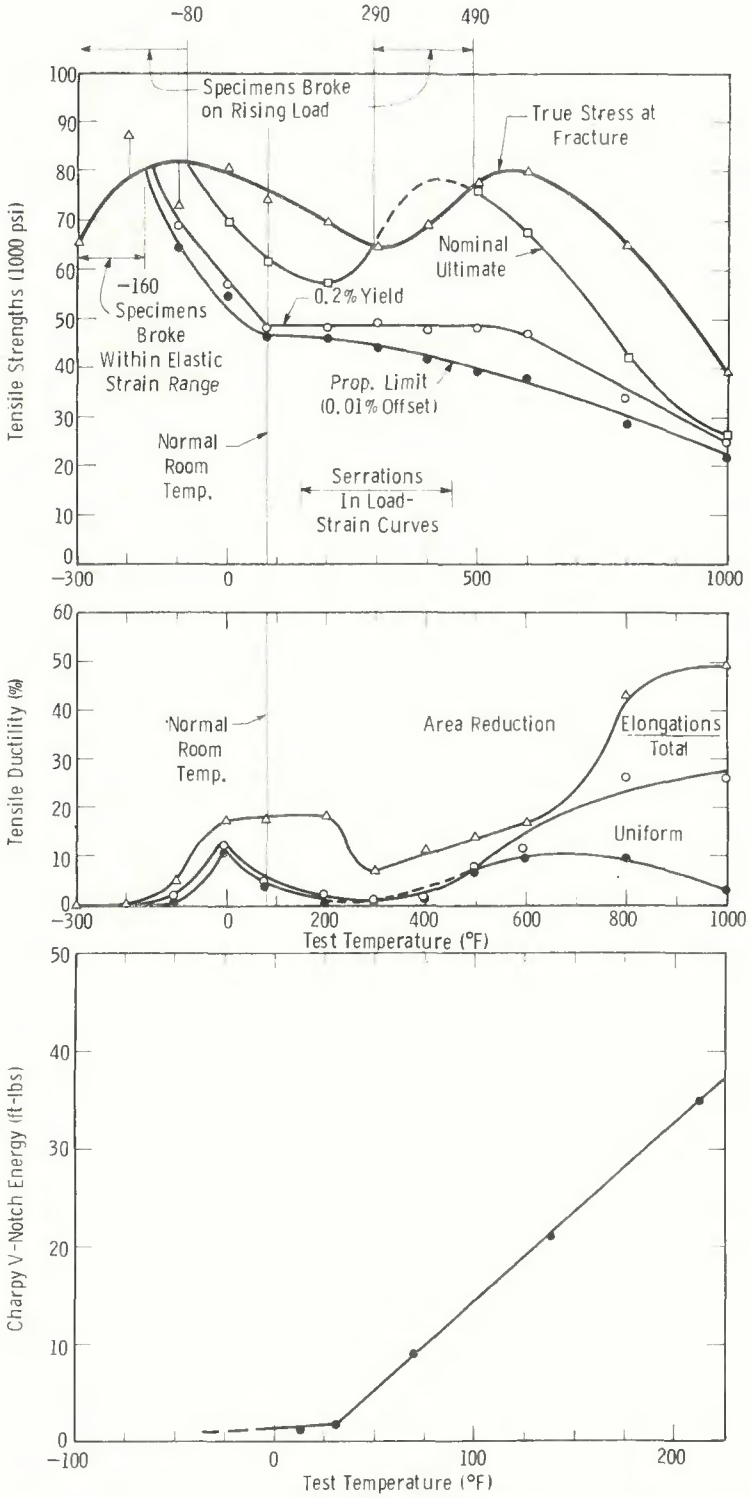

Fig. 8 — Temperature-dependence of tensile and impact properties for bare metal-arc as-deposited unalloyed steel weld metals

served in the area reduction values.

CO_2-Shielded, Flux-Cored. A series of 10 welds, made with representative flux-cored electrodes and carbon-dioxide arc shielding, provided 0.2% yield strengths ranging from 49,200 to 70,850 psi. The ultimate strengths increased at a uniform rate with the yield strength, the average being: U = Y + 15,160 psi.

The tensile ductility values progressively decreased with increased weld metal yield strength but remained at excellent levels (>25.7% total elongation and >53.6% area reduction) for the highest strength welds tested.

The weld metal composition ranges for the several elements were: 0.070-0.112C, 0.59-1.66Mn, 0.008-0.016P, 0.011-0.030S, 0.29-0.76Si, 0.026-0.10Cu, 0.002-0.028Ni, 0.024-0.061Cr, 0.005-0.017Mo, 0.006-0.019V, 0.0012-0.040Al, 0.0032-0.0108N, and 0.036-0.1243%O, by weight.

Unshielded, Flux-Cored. Welds made with the unshielded, flux-cored, metal-arc process contained higher than normal carbon (0.202-0.359%), nitrogen (0.050-0.074%), and, in some cases, aluminum (up to 1.87%) contents. However, the oxygen contents were usually low (0.0039-0.0060%).

The tensile strengths were about the same as for the CO_2 shielded,

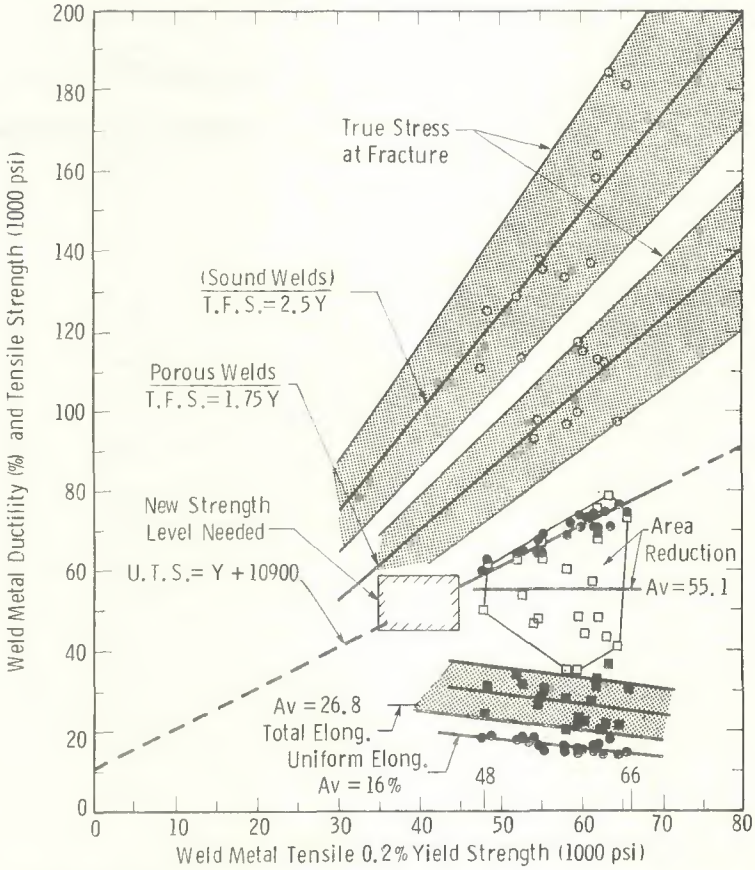

Fig. 9 — Interrelationships between tensile properties of covered electrode unalloyed steel weld metals

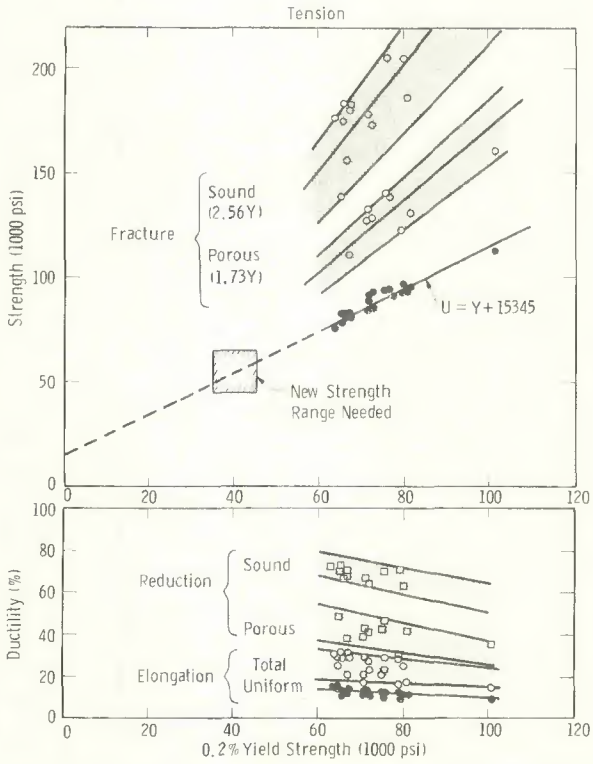

Fig. 10 — Mechanical properties of as-deposited argon-oxygen shielded metal-arc weld metals (unalloyed and copper bearing)

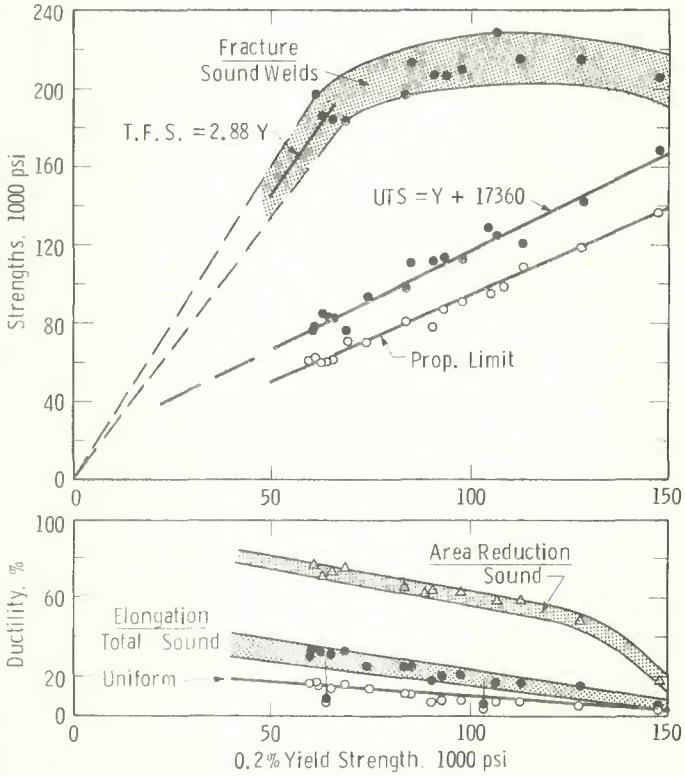

Fig. 11 — Tensile properties for alloyed weld metals deposited with 1960 commercial covered electrodes

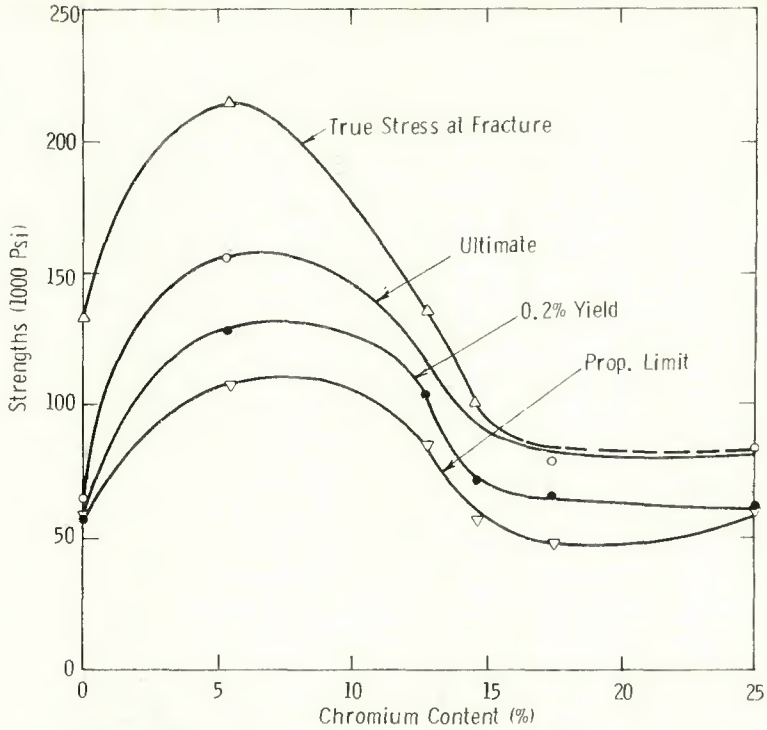

Fig. 12 — Chromium dependence of weld strengths (covered electrodes)

flux-cored electrodes, although the area reduction values were lower.

The true stress at fracture values were not recorded for these welds. Judging from the compositions, the area reduction values, and the impact values obtained, it is expected that those values would be low.

Submerged Arc. A series of six welds, made with the submerged arc process, using two different electrodes and two different flux compositions and characterized by having compositions of 0.037-0.105C, 0.90-2.21Mn, 0.012-0.025P, 0.012-0.017S, 0.21 -0.77Si, 0.003-0.007N, and 0.072-0.120%O contents, by weight, had yield strengths which ranged from 45,000 to 58,700 psi. The highest true stress at fracture value was 139,000 psi, or 3.0 times the yield strength. The ductilities were good (9.4-19.2% uniform elongation, 21-37% total elongation, and 34-70% area reduction).

Alloy Steels

Commercial Covered Electrodes. Covered electrodes for depositing metal-arc weld metals having yield strengths between 60,000 and 148,000 psi were commercially available prior to 1960.[21] These electrodes produced deposits having an average of 0.011P, 0.018S, 0.009N, and 0.033%O. The improvement of providing low nitrogen contents, one of the more significant advances made in covered electrodes, had gone largely unrecognized. The deposited welds otherwise had a wide range of compositions; all were based upon Fe, C, Mn, and Si, plus Ni, Cr, Mo, and/or V.

The as-deposited proportional limit and ultimate strengths increased linearly with the 0.2% yield strength — Fig. 11. The true stress at fracture to proportional limit ratios averaged 2.88:1.00 for the sound lower strength welds. Since there was little increase in the true stress at fracture for the higher strength welds, the ratio of true stress at fracture to proportional limit, as the yield strength increased, therefore progressively decreased — Fig. 11. The highest true stress at fracture value obtained was 229,400 psi for a 107,300 psi, 0.2% yield strength weld metal.

The tensile ductility values decreased progressively and linearly for 0.2% yield strength levels up to about 130,000 psi. For the higher strength welds the ductilities dropped rapidly — Fig. 11.

Commercial Covered Electrodes, Chromium. The chromium alloy steels illustrate the case where progressive additions of one element first increases and then decreases the tensile strengths, with little or no strength changes occurring at the composition levels of reversal, Fig. 12.[22]

In addition to chromium, these welds contained 0.04-0.10C, 0.48-0.81Mn, 0.011-0.026P, 0.010-0.025S, 0.18-0.71Si, 0.09-0.12Cu, 0.08-0.51Ni, 0.03-0.52Mo, 0.03-0.24V, 0.007-0.11N, and 0.046-0.112%O, by weight.

Covered Electrodes, Experimental, Air-Melted. A 1961 series of 39 air-melted, experimental compositions were drawn into filler metal, extrusion covered with commercial E-7018 and other type mixtures, and used for making test welds — Fig. 13. The filler metal and coating compositions were such that the weld deposits ranged from low amounts of each element up to 0.19C, 5.94Mn, 1.36Si, 2.50Cu, 4.54Ni, 3.88Cr, 2.05Mo, 0.74V, 2.18Co, 0.74W, 0.57Cb, 0.15Ti, 0.024Zr, and 0.25%Al. The average P, S, and N contents were 0.011, 0.018, and 0.009%, respectively. The oxygen content varied from 0.016 to 0.089%, by weight.

These deposits provided tensile 0.2% yield strengths of 91,000 to 163,400 psi. The sound welds had tensile properties similar to those already described — that is, the proportional limit was 0.901 times that of the 0.2% yield strength, and the ultimate tensile strength was equal to the yield strength plus 18,345 psi. The true stress at fracture values were almost always above 200,000 psi, but never exceeded 269,800 psi. The low true stress at fracture values resulted in ratios of that value to the proportional limit which were almost always less than 2.0. The differentials between the two values ranged from 64,800 to 123,000 psi, for sound welds.

The total elongation values exceeded 13%. The area reductions exceeded 43%. This is moderate but not good ductility.[23]

Covered Electrodes, Experimental, High-Purity, Vacuum-Melted. The 1962 results obtained from a series of 53 weld deposits made from experimental compositions of high-purity, vacuum-melted filler metals after extrusion with commercial mixtures of E-7018 and various other type coverings were not significantly better than those obtained from the air-melted wires just described. Part of the observed improvements could be credited to somewhat lower alloy contents. There was little difference in the P, S, N, and O contents of the welds for the two series of tests. The average oxygen content of these welds was 280 ppm (0.0280%), and the average nitrogen content was 96 ppm (0.0096%). The obtained results demonstrated the need for further modifications in electrode coatings so that weld deposits having low oxygen contents might be produced.[23]

The relations between the several strength and ductility indexes of these welds and their respective 0.2% yield strengths are nearly

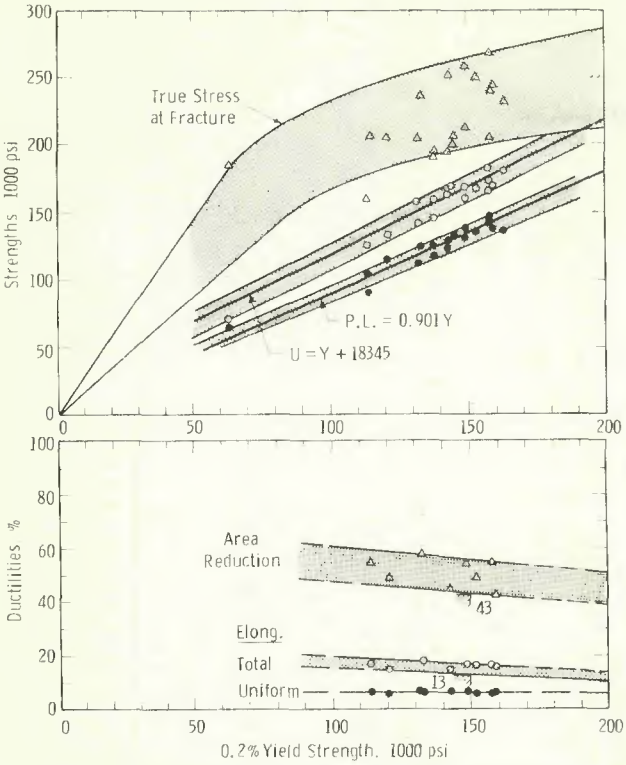

Fig. 13 — Tensile properties of welds made with air-melted filler metals and low hydrogen iron powder type coverings

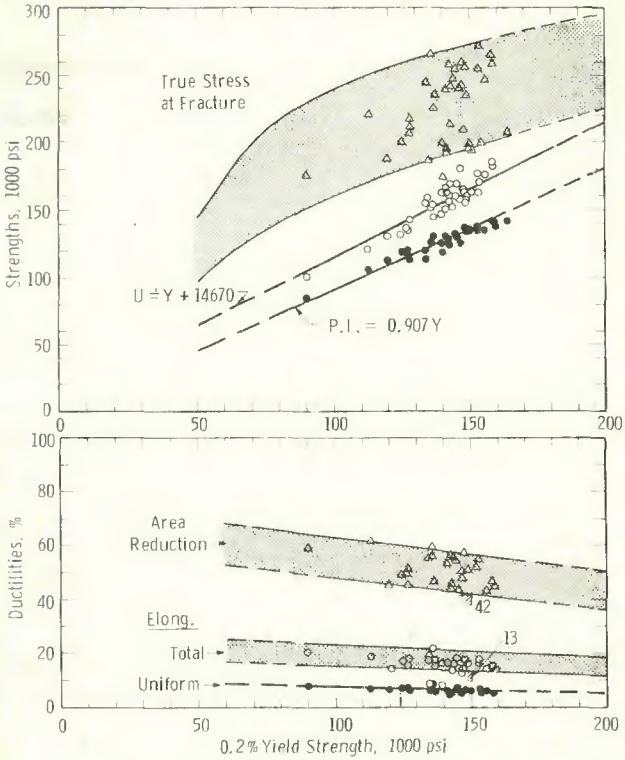

Fig. 14 — Tensile properties of welds made with high-purity vacuum melted filler metals and low hydrogen iron powder type coverings

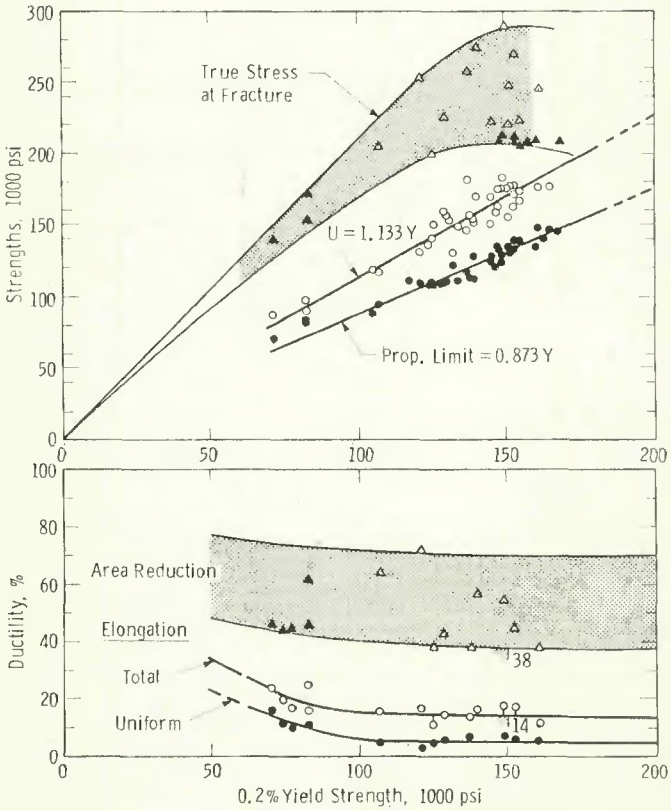

Fig. 15 — Tensile properties of metal-arc welds made with air and vacuum melted, lightly coated electrodes, in an argon shield

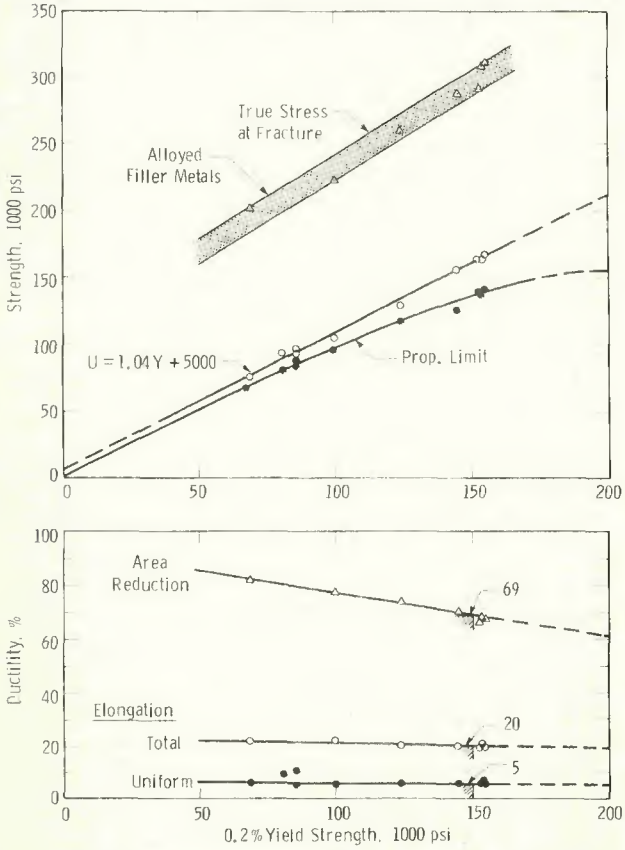

Fig. 16 — Tensile properties for helium shielded metal-arc welds made with high purity bare filler metals

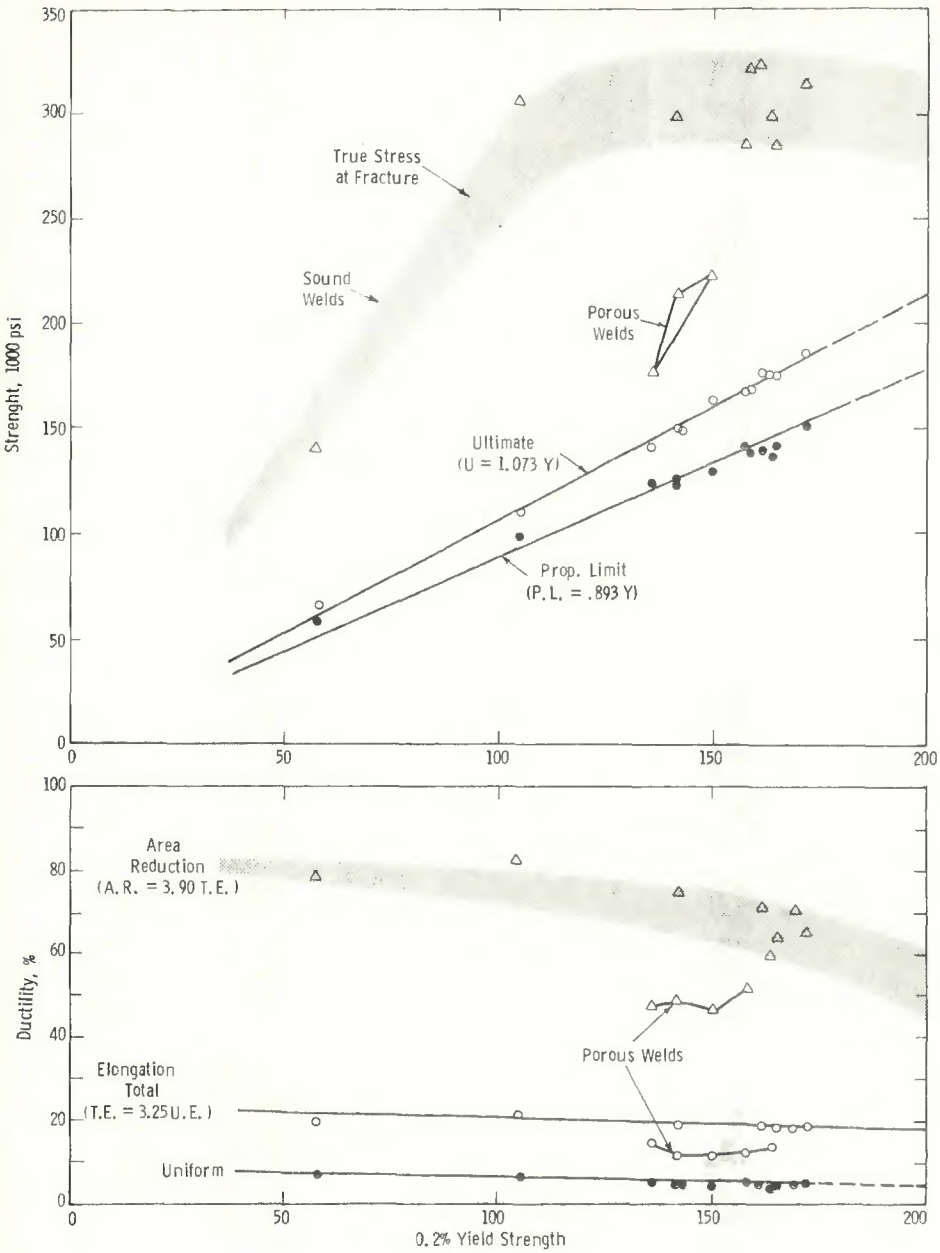

Fig. 17 — Tensile values for open-room gas tungsten-arc welds

identical with those obtained from the air-melted filler metals, Fig. 14. The deposit compositions were such that the 0.2% yield strengths ranged from 67,000 to 160,000 psi. A few of these welds contained tungsten, cobalt, columbium, and zirconium as additional alloying elements.

Lightly Coated, Experimental Compositions, Argon-Shielded. A series of 71 welds was made using filler metals produced from the same experimental ingots as used for the preceding two sets of air-and vacuum-melted covered electrodes. The rods were drawn down to 0.062 in. diameter coiled wires which were then lightly coated with an oxide slurry before usage. Argon (99.999%) was used as a shielding medium. The 0.2% yield strengths of the weld deposits ranged from 72,000 to 172,000 psi — Fig. 15. These welds were characterized by having relatively low tensile ductilities. The average oxygen content was 185 ppm, originating from the applied coatings. The nitrogen contents ranged from 17 to 420 ppm, depending upon the stability of the arc.

In a companion series of 13 welds, made with both commercial and experimental bare surface compositions but using a 99%A-1%O_2 shielding mixture, the deposits ranged from 75 to 620 ppm in oxygen content and from 15 to 130 ppm in nitrogen content. The 0.2% yield strengths ranged from 81,000 to 168,000 psi. None of these welds exhibited high ductility values.

Helium-Shielded, Metal-Arc. Helium shielding provided a means for operating a stable arc while, at the same time, producing smooth weld bead surfaces which, in turn, permitted the deposition of sound, multipass welds. These deposits, in general, contained less than 40 ppm oxygen and less than 20 ppm of nitrogen when made under ordinary open room conditions.

The 0.2% yield strengths in this series ranged from 69,000 to 155,000 psi — Fig. 16. For the first time, true stress at fracture values in a gas metal-arc weld of more than 300,000 psi were obtained. The smallest total elongation value observed was 18.75% and the smallest area reduction value was 67.30%.

Vacuum-Melted, Experimental Compositions, Open Room, Argon-Shielded, Tungsten-Arc. The series of 18 filler metals of differing compositions was used with conventional cold-wire-feed — that is, electrically neutral filler metal with the gas tungsten-arc process. The 0.2% yield strengths of the resulting welds ranged from 58,300 to 198,500 psi. The oxygen contents of these deposits ranged from 1 to 40 ppm (0.0001 to 0.0040%) and the nitrogen contents ranged from 10 to 51 ppm (0.0010 to 0.0051%).

The true stress at fracture for several of these welds exceeded 300,000 psi. The maximum value was 348,000 psi — Fig. 17.

Vacuum-Melted, Experimental Compositions, Argon-Shielded, Tungsten-Arc in Dry-Box. To achieve the ultimate in efficiency for shielding the arc and molten metal against contamination from oxygen, nitrogen, and hydrogen, the series of 122 welds was made within the confines of an evacuated, purged, and argon-filled chamber. The compositions of the filler metals used included those already described, but included others which varied over wide ranges to produce weld deposits having 0.2% yield strengths from 41,700 to 207,000 psi. True stress at fracture values as high as 374,500 psi were obtained — Fig. 18.

This series conclusively demonstrated that high toughness can be produced in alloy steel welds having high strengths.[24] Such welds tend to have high true stress at fracture values in the tensile test and a wide differential between the true stress at fracture and proportional limit values.[25] This series also demonstrated that the essentially complete removal of oxygen, nitrogen, and

hydrogen from the weld deposits is not an exclusively unique condition for assuring the production of high toughness deposits. A proper alloying content must be used to assure the production of high toughness weld metals. Best results were obtained when the weld check analyses for carbon contents were less than 0.14%. Even lower maximum limits for carbon were required for some alloy compositions. Also, best results were obtained when the manganese content approached zero, while at the same time, the chromium, molybdenum, and vanadium contents were not excessively high and the aluminum, columbium, titanium, and zirconium contents were low.

One consequence of these tests was the conclusion that an Fe-5%Ni-2%Mo-C alloy system would have outstanding strength and toughness characteristics. By using carbon as the only variable, quality control can be readily maintained. A simple check analysis for each heat or lot would assure consignment to the proper weld strength grade.[26] The test results from such a series are shown in Fig. 19.

The average nickel content for this series of welds was 4.49%. The average molybdenum content was 2.03%. All other elements, except carbon, were low: 0.01-0.05Mn, 0.0005-0.0038P, 0.0019-0.0038S, 0.01-0.04Si, 0.01-0.13Cu, 0.12-0.20Cr, 0.01-0.02V, 0.0010-0.0026N, and 0.0003-0.0014%O.

The carbon content was varied from 0.082 to 0.32%. The 0.082%C content deposit provided a 0.2% yield strength weld of 131,100 psi. The proportional limit was 126,000 psi. The corresponding true stress at fracture was 321,500 psi. The strength increases and the ductility decreases, as shown in Fig. 19, are caused solely by changes in carbon.

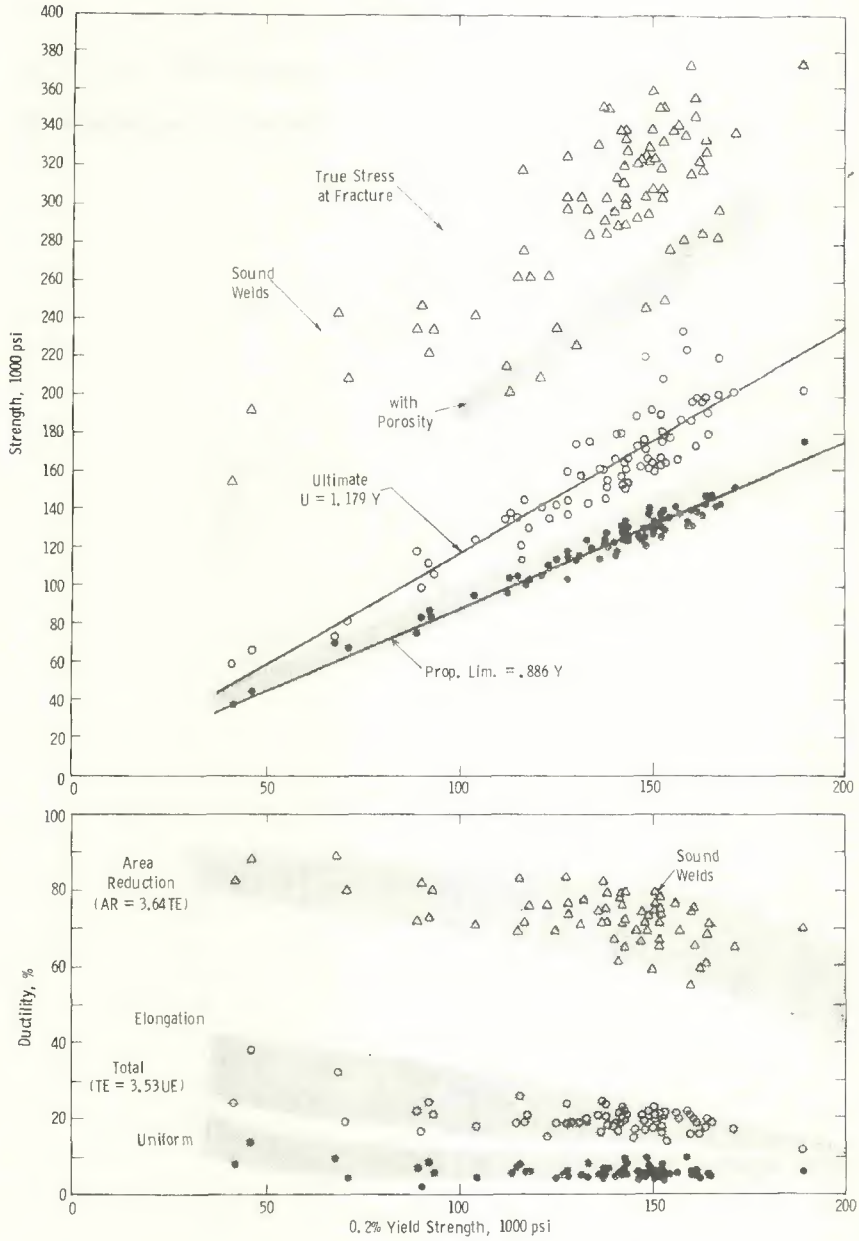

Fig. 18 — Tensile properties for dry-box weld metals made with air and vacuum melted filler metals (gas tungsten-arc)

Impact Properties of Welds

Iron

The high impact energy absorption of pure iron weld metals, which was 240 ft-lb at test temperatures between −10 and +200 F, correlates with the relatively high ratio of true stress at fracture to proportional limit stress, i.e., 3.81:1. The absorbed energy values degraded abruptly to about 10 ft-lb at −20 F, and below — Fig. 7, right view. No cleavage facets were visible at temperatures of −10 F, and above, whereas at −20 F, and below, the impact fractures were 95%, or more, cleavage.

Unalloyed Carbon Steels

Bare, Metal-Arc. Charpy V-notch impact energy values decreased from 35 ft-lb at +200 F to 2 ft-lb at +32 F. The low impact energy values are directly related to the cumulative effects of the high nitrogen (nitride) and oxygen (oxide) contents, which cause a small differential between the tensile true stress at fracture and proportional limit values (TFS:PL = 1.55:1, or TFS-PL = 26.200 psi); Fig. 8.

Covered Electrodes. Impact data over the +200 to −100 F range are available for only six of the 1950 test welds described, but these cover the entire tensile strength range. The impact energy values decreased with increasing yield strength at a rate which demonstrated that high toughness welds could not be obtained in the unalloyed covered electrode system when the yield strength exceeded about 65,000 psi — Fig. 20B. The weld having the highest true stress at fracture in the tensile test (185,200 psi) had the highest impact energy value (240 ft-lb at +80 F).

The oxygen content of the weld metal influenced the impact energy absorbed; the higher the oxygen content the lower the impact energy — Fig. 20A. Increases in oxygen contents also lowered the fracture appearance transition temperature (FATT) values. This is explained by the fact that the FATT values increased with increasing yield strengths and, with the higher strengths and high oxygen contents, grain boundary and not cleavage separations occurred.

Argon-Oxygen Shielded, Metal-

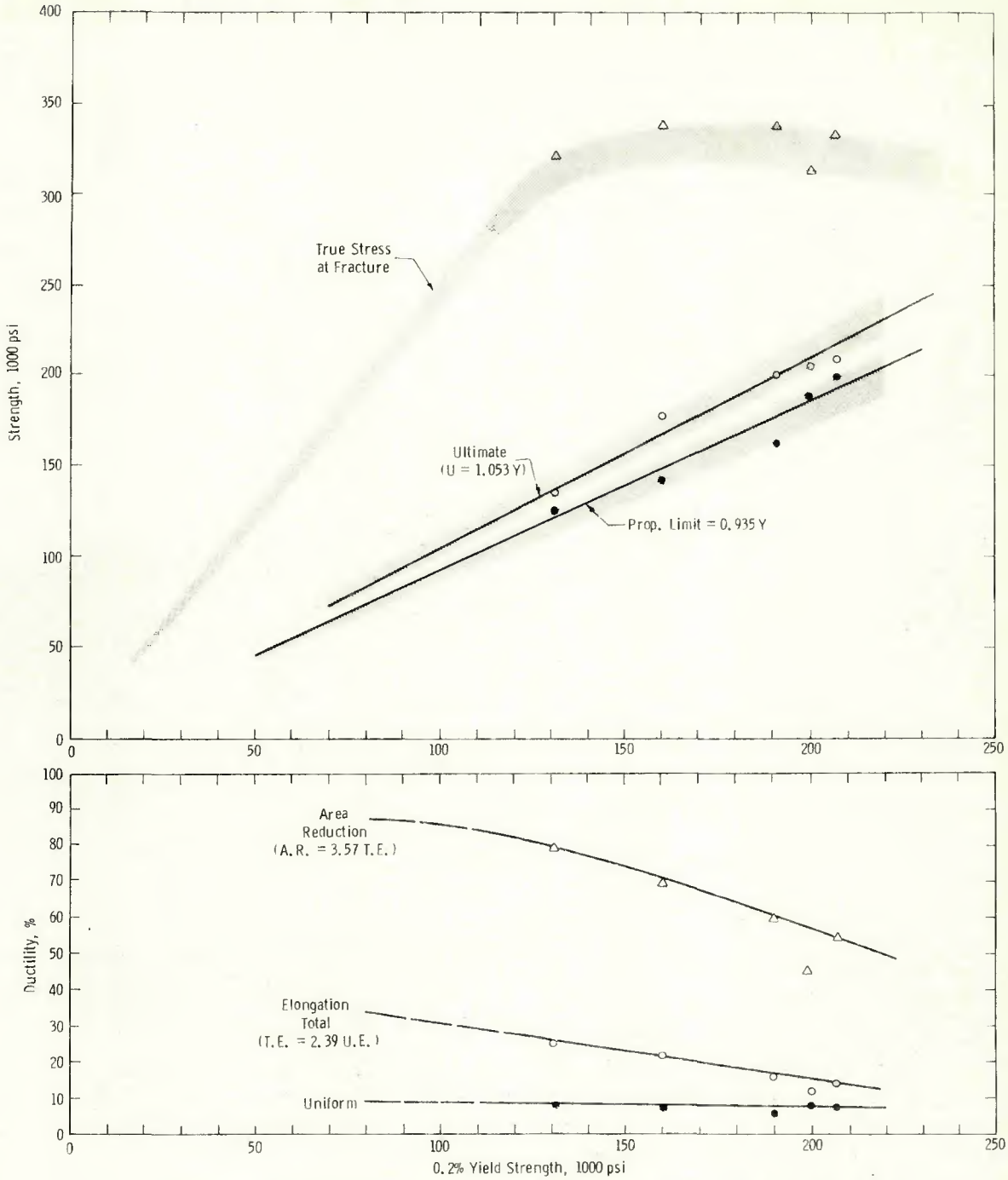

Fig. 19 — Tensile properties of 5% Ni–2% Mo argon shielded, tungsten-arc weld metals

Arc. The room temperature Charpy V-notch impact energy values for the non-copper bearing argon-oxygen shielded welds decreased drastically with increased yield strength — Fig. 21. This indicates that the degradation was related to some other factor, such as oxygen, in addition to the yield strength.

By plotting the impact energy values from both the +80 and –20 F tests as response variables of the carbon contents, it will be shown (Figs. 37 and 38) that both the non-copper and copper-bearing welds conform to the Fig. 6 toughness model. The copper-bearing deposits, for a given carbon level, have superior impact toughness at each of the two test temperatures as compared with the non-copper bearing deposits. The improvement is particularly significant at –20 F.

The FATT values for the copper-bearing welds decreased as the yield strength increased — that is, the impact specimens having the lesser energy absorption exhibit lower, and therefore preferred, FATT values!

CO_2-Shielded, Flux-Cored. The impact energy values decreased rapidly with increased yield strength, and the FATT values increased rapidly for yield strengths above 57,000 psi. Since, except for oxygen contents, the compositions of all these welds were similar, it was concluded that the impact energy values were primarily dependent upon the oxygen contents — Fig. 43. These ranged from 0.036 to 0.1243%. The nitrogen contents of all these welds were low,

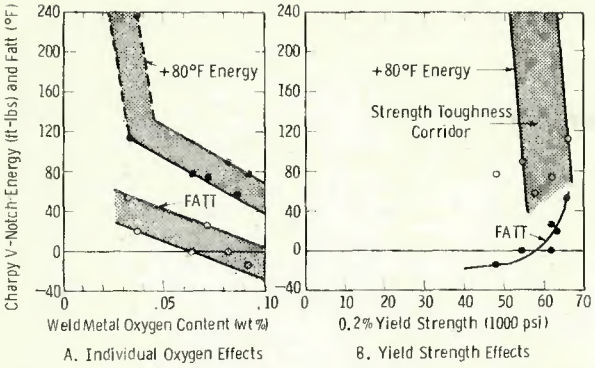

Fig. 20 — Oxygen content and strength dependence of impact energy and FATT values for covered electrode unalloyed steel weld metals (C .057/.10; Mn .28/.78; Si .06; N .007/.019)

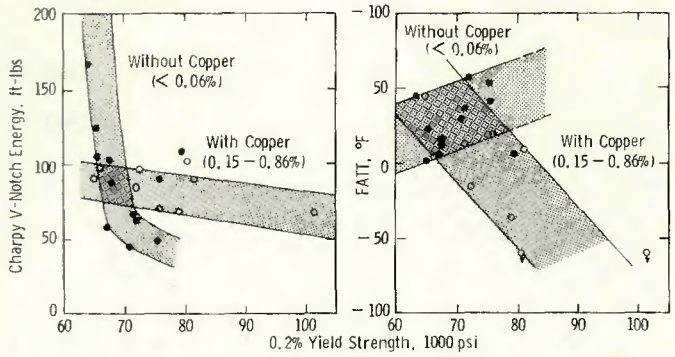

Fig. 21 — Energy and FATT dependence upon strength for carbon steel 99%Ar-1% O_2 shielded metal-arc weld metals

the average value being 0.0065%.

Unshielded, Flux-Cored. The impact energy values were low (26 ft-lb at +80 F) and the FATT value was high (+132 F). The low toughness and the high FATT value are the consequence of the higher carbon, nitrogen, and in some cases, aluminum contents.

Submerged Arc. The impact energy values were from 27 to 52 ft-lb at room temperature, which is relatively low considering the 2.76:1 ratio of the true stress at fracture to the proportional limit. These lower impact energy values result from the higher manganese, silicon, and oxygen contents, together with the larger grain size commonly obtained with the use of this process.

Alloy Steels

Commercial Covered Electrodes. The impact energy values of the 1960 electrode welds at +80 F progressively decreased from 118 ft-lb for the low yield strengths to about 15 ft-lb for the 148,000 psi yield strength welds. The primary cause of degradation in impact energy values was the higher carbon and oxygen contents, which, in part, were responsible for the low true stress at fracture to proportional limit ratios.

The FATT values increased rapidly and somewhat irregularly as the yield strength increased. From inspection of the data, the highest FATT values, above +100 F, were obtained for those welds containing more than 2%Cr, whereas the lowest FATT values were obtained from welds which contained essentially no chromium. High (0.18%) carbon contents tended to produce high FATT values. Also, vanadium contents above 0.20%, in the presence of more than 0.021% oxygen, raised the FATT values. The presence of higher amounts of manganese favored lowering the FATT values. The presence of nickel was not necessary to produce low FATT values, although 60% of the lower FATT values were obtained with welds having more than 2%Ni.

Covered Electrodes, Experimental, Air-Melted. All of the iron powder, low hydrogen type coating, impact energy values were low, the range being from 4 to 44 ft-lb at +80 F.

The FATT values were nearly all above room temperature and were inversely related to the impact energy values; that is, they were raised as the weld metal yield strength increased. The highest FATT values (>+200 F) were obtained with welds containing Cb and Ti, over and above the basic Ni-Cr-Mo-V compositions. This indicates that titanium contents of 0.068%, and above, and columbium contents of 0.28%, and above, must be avoided.

The average oxygen content of the welds in this series, exclusive of those made with other than the E-XX18 type coatings, was 0.0292%. Two low (0.05-0.06%) silicon content welds having high (0.076 and 0.089%) oxygen contents had FATT values near room temperature. A weld made with a different type coating, which also resulted in a high (0.066%) oxygen content, had the lowest FATT value (–26 F). Thus, the data from this series also indicate that FATT values are lowered by increased oxygen levels, because failure occurred at oxidized grain boundaries instead of by cleavage.

Covered Electrodes, Experimental, High-Purity, Vacuum-Melted. The impact results for the vacuum-melted series of covered electrode welds were not significantly better than those obtained from the air-melted filler metals. The highest individual impact energy value at +80 F was 45 ft-lb for a 134,000 psi tensile yield strength weld.

From these studies, it was concluded that improved impact values would not be obtained until the Mn, Si, and O contents of the weld deposits were grossly reduced.[23]

Lightly Coated, Experimental Compositions—Argon-Shielded, Metal-Arc. Only 4 of the 59 lightly oxide-coated, argon-shielded, metal-arc welds provided impact energy values of more than 40 ft-lb at room temperature. These welds had 0.2% yield strengths between 120,600 and 161,300 psi. The poor results were caused by the degrading effects of the weld metal oxide contents, from the coating, superimposed upon the bulk metallic composition effects.

Helium-Shielded, Metal-Arc. The helium-shielded metal-arc welds, made with electrodes having all elements increasing at once, exhibited high (>100 ft-lb) impact energy values for all yield strength levels below 125,000 psi. A vanadium-free composition, which provided a yield strength of 153,600 psi, produced a weld having 70 ft-lb energy at +80 F — Fig. 22.

The FATT values increased with increased yield strengths, the reverse of the energy values. This is the same relation observed for the covered electrode unalloyed steel welds — Fig. 20B.

Vacuum-Melted, Experimental Compositions, Open Room, Argon-Shielded, Tungsten-Arc. The impact energy values for many of these welds were remarkably good, being as high as 100 ft-lb for a deposit having a yield strength of 172,000 psi. That weld had a true stress at fracture value of 315,600 psi, and an oxygen content of 0.0007%.

The presence of silicon in three of the welds in this series tended to lower the energy absorbing capabilities and to raise the FATT values — Fig. 23. The FATT values have the same relation to the yield strength as for the consumable electrode welds.

Vacuum-Melted, Argon-Shielded, Tungsten-Arc in Dry-Box. Excellent impact results were obtained from

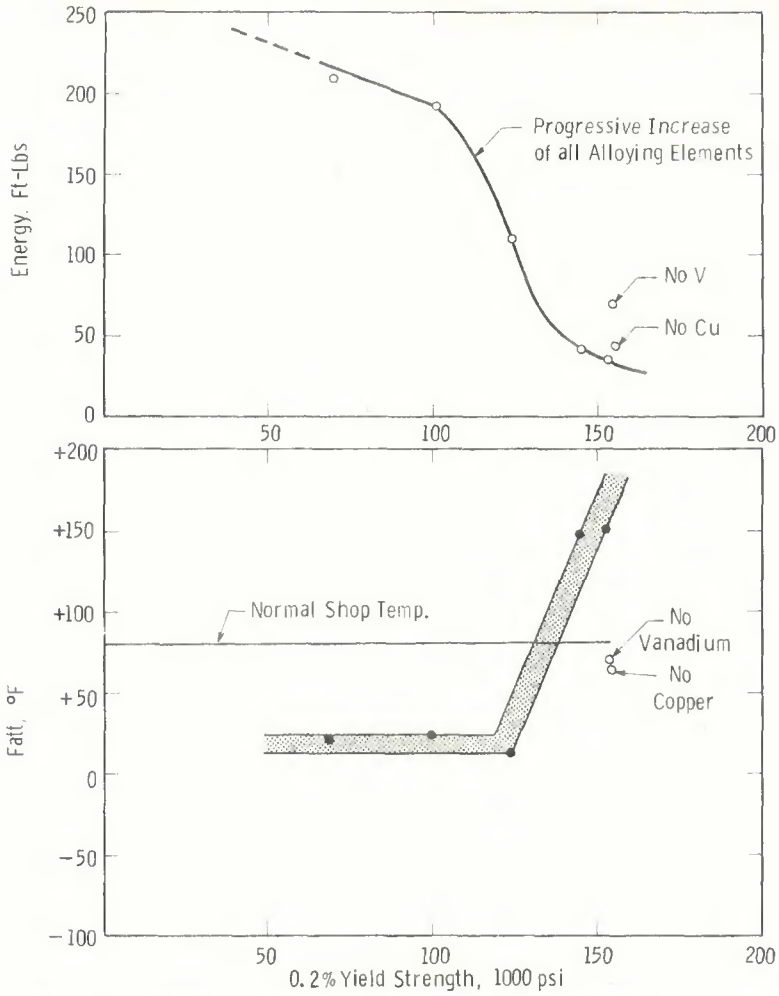

Fig. 22 — Dependence of impact values on tensile yield strength for open-shop gas metal-arc welds (helium shielding)

the in-chamber tungsten-arc welds. This was not the exclusive consequence of the fact that these welds were made by remelting high-purity, vacuum-melted rods, or that the oxygen contents were extremely low (<10 ppm in many cases). To obtain high toughness, high strength weld metals, other components of the alloy system must also be present, or absent, in appropriate amounts. This is illustrated by the data in Fig. 24. There the results of 81 test welds were grouped to show that within the 80,000 to 130,000 psi yield strength range, even when using vacuum-melted, high-purity filler metals and making the welds in a sealed, evacuated, purged chamber filled with high-purity argon, so that there was no possibility of contamination by nitrogen, oxygen, or hydrogen, the resulting impact energy values varied from 240 to 20 ft-lb at room temperature. Even lesser values were obtained when Al, Cb, Ti, and Zr were added to the test compositions. The high energy absorbing weld metals were those containing low carbon and low manganese, with other elements (Cu, Ni, Cr, Mo, V, W, and Co) properly balanced, whereas the low energy content welds contained high amounts of carbon, manganese, molybdenum, zirconium, titanium, columbium, or aluminum.

In a corresponding manner, and consistent with the previously described relations, the FATT values also varied widely over the same strength range — Fig. 25. The welds containing low carbon, low manganese, and those which were free of such elements as columbium, titanium, and zirconium were the ones having the low (i.e., desirable) FATT values.

Impact values for the previously discussed Fe 5Ni-2Mo-C welds were high (240 ft-lb) for yield strength levels of 130,000 psi and below, and were fair (29 to 45 ft-lb) at 200,000 psi yield strength level — Fig. 26 FATT values of below -200 F were obtained for 160,000 to 190,000 psi yield strength welds — Fig. 26.

Interrelationships Between Tensile and Impact Values

The general relationship between Charpy V-notch impact energy and tensile yield strength values at room temperature is: the energy values tend to be highest at the low strength levels and vice versa.[27,28] It is possible to obtain high impact energy absorbing capabilities and high yield strengths by using alloying strengthening elements other than carbon, manganese, and silicon, and by keeping the P, S, N, O, Al, Cb, Ti, and Zr contents very low.

The toughness of a metal may be judged, in part, by the ratio of the true tensile stress at fracture to the corresponding proportional limit value. Such values, for covered electrode, gas metal-arc, and gas tungsten-arc welds, are shown in Fig. 27. The gas tungsten-arc welds had higher true stress at fracture to proportional limit ratios for any given yield strength. The better gas metal-arc welds were as good or better than the poorer gas tungsten-arc welds. For 0.2% yield strengths below about 80,000 psi, equivalent ratios were obtained with all processes, although the trend was for lower magnitude ratios with the metal-arc processes, particularly for the higher strength welds.

The dependence of the impact energy values upon the ratios of true stress at fracture to proportional limit are shown in Figs. 28 and 29. When the ratio was three, or more, the impact energy values were near or above 200 ft-lb. When the ratio decreased to a value approaching two, or less, the impact energy values were low.

The data in Fig. 29 demonstrate the powerful effect of manganese and carbon on impact values. Best results were obtained both in the ratio of true stress at fracture to proportional limit and in impact energy values by complete removal of the manganese and by use of low carbon contents. Conversely, increasing the manganese to about 2%, and above, reduces the welds to a brittle condition. Continuous additions of carbon lower both the true stress at fracture to proportional limit ratio and the impact energy values.

Similar plots were made for every process-alloy variation combination tested. In every case, there was a tendency to follow the same patterns as shown in Figs. 28 and 29. However, in several instances, as for the covered electrode and lightly coated filler metals, all of the test points became concentrated in the lower left corner, that is, the energy values were low and the true stress at fracture to proportional limit ratio values were generally less than 2.0.

A mirror image of Figs. 28 and 29 shows that once the ratio of true stress at fracture to proportional limit decreases below about 3, the impact energy values rapidly deteriorate. Since it was shown in Fig. 27 that that ratio is related to the yield strength, this is the equivalent of saying that the degradation in impact values with increased yield strength is the direct consequence of lowering the true stress at fracture to proportional limit ratio. Despite this relationship, few investigators working on the attainment of higher strength, high toughness weld metals are even measuring true stress at fracture values, the most critical variable in the entire problem.

Examining the true stress at fracture and proportional limit relationships from the point of view of differences in their magnitudes, the effects are even more striking. Such differences are related to the yield strength for open shop, gas tungsten-arc welds in Fig. 30. In that series, alloying additions were increased so that as the yield strength rose to about 130,000 psi, the maximum differential, in the vicinity of 200,000 psi, was obtained. Further addition of alloys, which again raised the yield strength, resulted in a rapid deterioration of the differential between true stress at fracture and proportional limit.

For other alloying systems and process combinations, the patterns were similar, although the magnitudes of the yield strengths and the stress differentials varied. For example, with the unalloyed carbon steel system, the peak difference between TFS and PL occurred at a yield strength of about 50,000 psi, the stress differential being 100,000 psi — Fig. 31. For the alloy steel systems, as the true stress at fracture strength and proportional limit differences increased above 100,000 psi, the impact energy values increased rapidly (Fig. 31) and as the strength differentials approached and exceeded 200,000 psi, the impact energy values were, in general, above 200 ft-lb. Once again, this graph illustrates the potent effect of manganese on weld fracture strength and impact energy.

When the two knuckles of the gas tungsten-arc scatter band values in Fig. 31 are connected to the 0-0 point with straight lines, the triangle thus created encloses the data points for the lightly coated, argon-shielded metal-arc and the covered electrode alloy steel weld metals.

The corresponding values for the bare metal-arc welds are shown by the dot at the lower left of the diagram. These values also would be encompassed in the same scatter band.

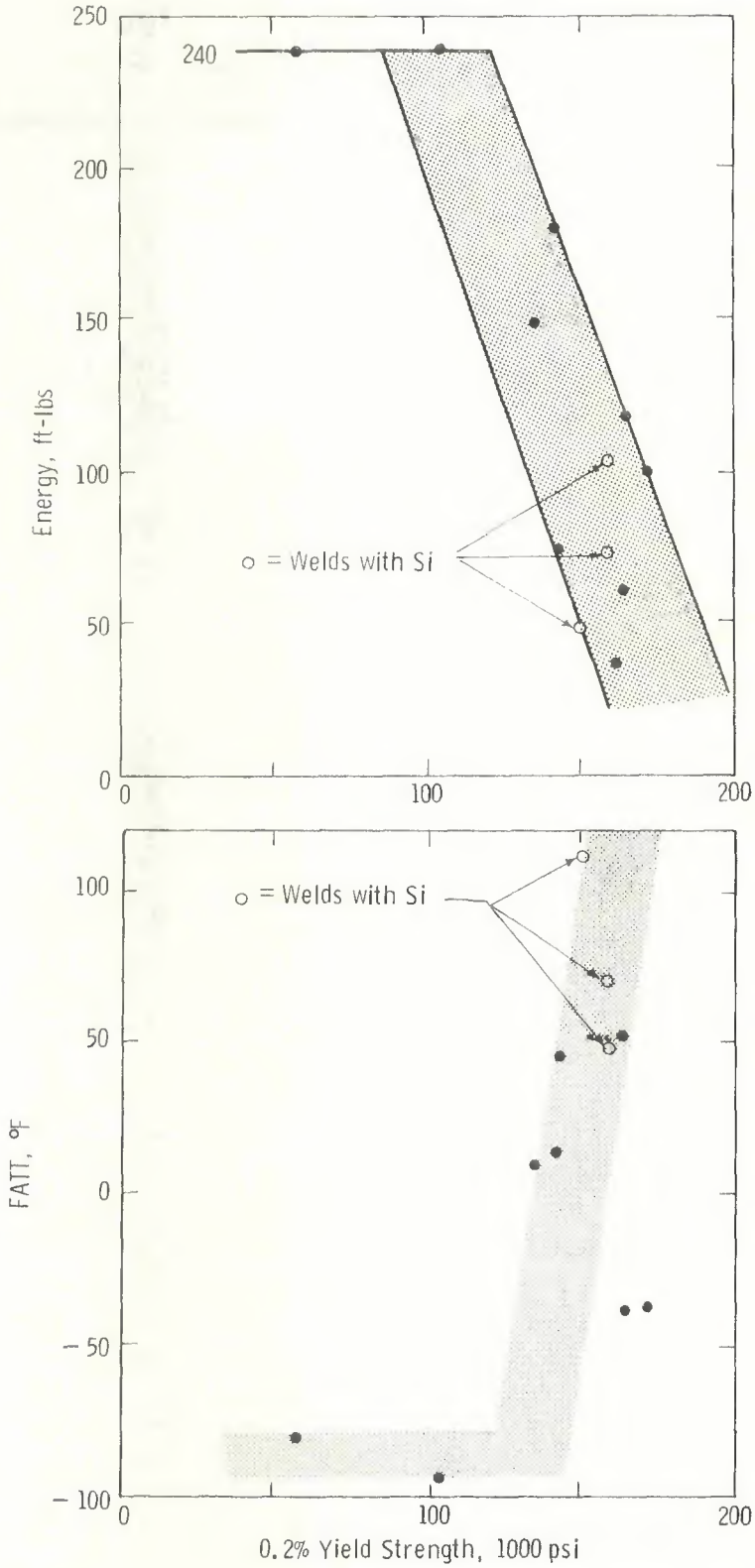

Fig. 23 — Impact values for open room argon shielded tungsten-arc welds

The magnitudes of the impact energy values obtained for a given differential between true stress at fracture and proportional limit are entirely different for the unalloyed steels (left scatter band of Fig. 31) and for the low oxygen content alloyed steel welds (right scatter band). The values for the pure iron, gas metal-arc weld, as shown in Fig. 7, fall on the upper part of the unalloyed covered electrode steel scatter band of Fig. 31.

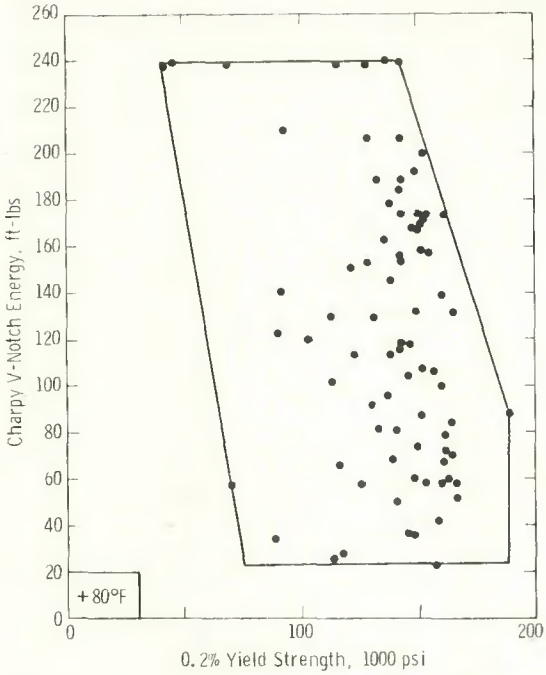

Fig. 24 — Impact energy values for dry-box gas tungsten-arc welds made with vacuum melted filler metals of widely varying compositions

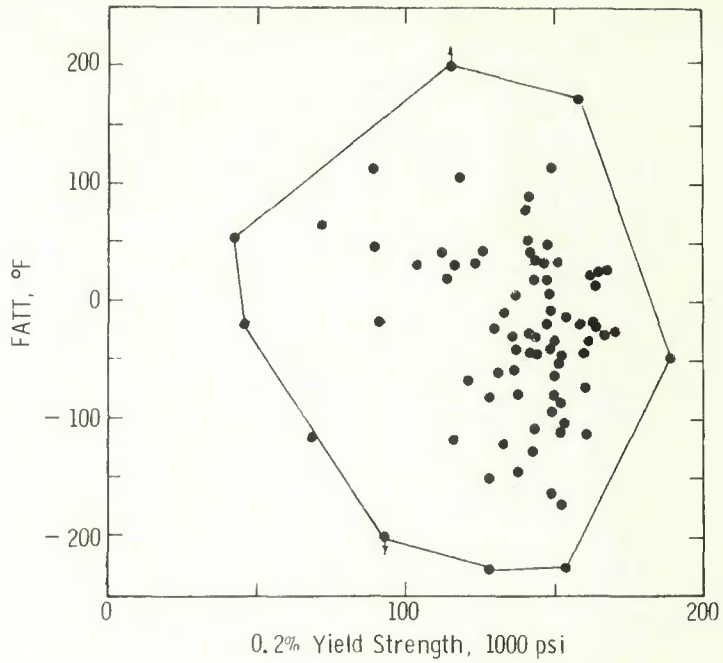

Fig. 25 — Impact FATT values for dry-box gas tungsten-arc welds made with air and vacuum melted filler metals of widely varying compositions

For each alloy system and welding process, as the alloy and impurity contents are altered to produce higher energy levels in the impact test, the FATT is suppressed — Fig. 32. This general relationship is true for all alloy systems and processes investigated, although the specific magnitudes vary.

The existence of low oxygen contents is a necessary but not an exclusively sufficient condition to assure the production of high impact energy and low FATT values in steel weld metals. A proper alloy balance also must be maintained.

For this presentation, it was necessary to confine discussions of weld metal toughness to Charpy V-notch impact energy absorption values. It can be demonstrated that the higher Charpy impact energy values obtained correlate with higher Dynamic Tear Energy values — Fig. 33.

Composition Dependence of Mechanical Properties

The individual influence of each element, within its useful range, upon both strength and toughness can be demonstrated.

Carbon

Carbon may increase the yield strength in any one of three specific forms:

1. With a multiplying coefficient on a continuous linear basis, Fig. 34, as was found for the welds described by Fig. 19.

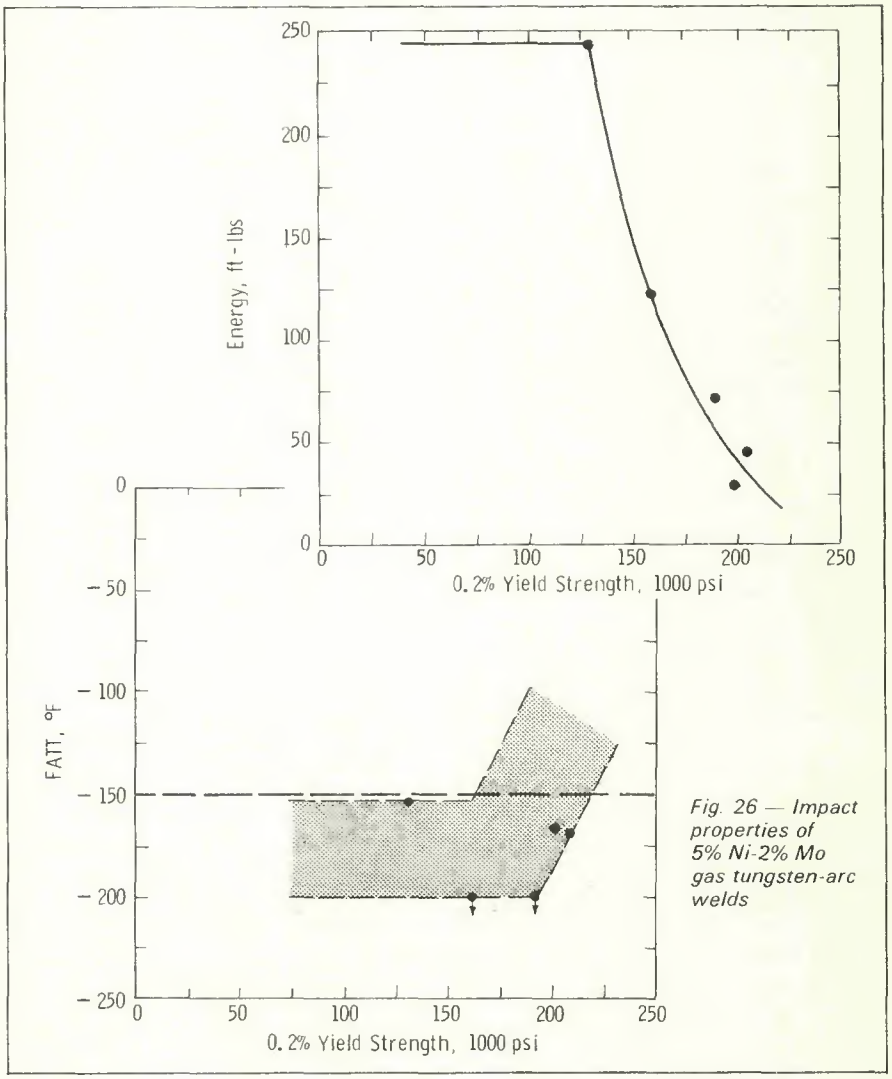

Fig. 26 — Impact properties of 5% Ni-2% Mo gas tungsten-arc welds

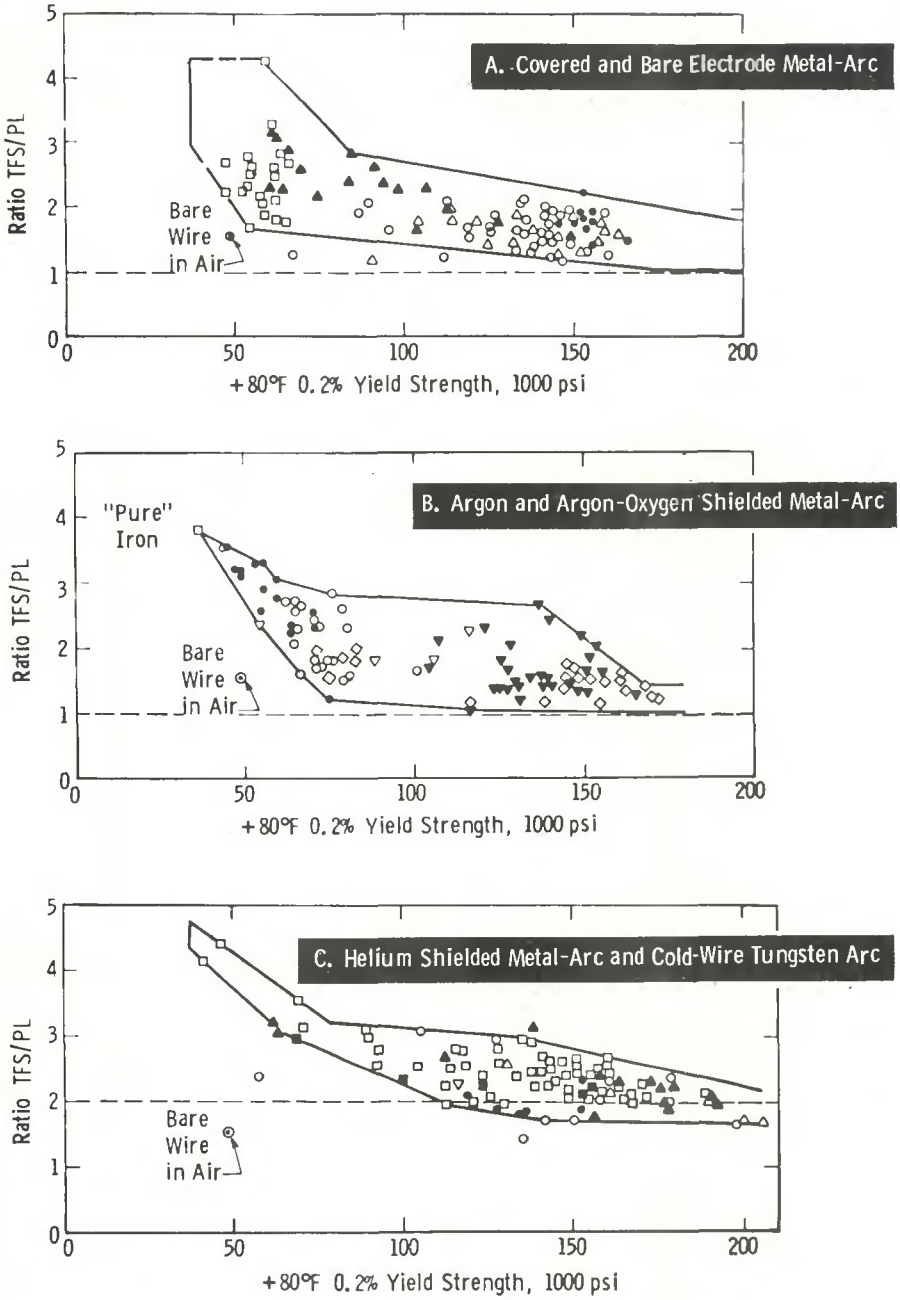

Fig. 27 — Relations of ratio of T.F.S. to P.L. and 0.2% yield strength

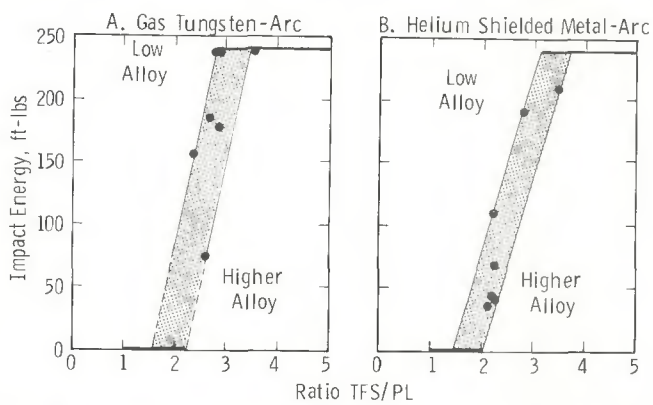

Fig. 28 — Dependence of impact energy values upon ratio of T.F.S. to P.L. for gas tungsten-arc and helium shielded metal-arc welds

2. As a square root function (Fig. 35A) as was found for the welds described by Fig. 1.

3. As a binomial function, Fig. 36.

The first two relationships imply that the yield strength increases continuously, regardless of the amount of carbon present. This presumption is probably incorrect. The last two relationships imply that small additions of carbon tend to have a more potent effect upon strength per unit of added weight than for similar higher level additions. This is probably true. Over the broad range, the Fig. 36 binomial summation for the effect of carbon appears to be the most acceptable form. However, for practical purposes, and within the 0.04 to 0.14% carbon content range, there is little error in considering that carbon increases yield strength in a linear relationship.

In practice, steel weld metal carbon contents seldom exceed 0.25%, and usually should not exceed 0.10%. The differences in results for the three potential form interrelations over these narrow ranges do not produce major differences in the conclusions. Final selection of the preferred form to provide the best fit for all available experimental data will depend upon the output of mathematical computerized studies now in progress.

Carbon additions in unalloyed steel welds are less productive, per unit weight, in increasing strengths than in alloyed steels (compare Fig. 35A with Figs. 34 and 36). For example, when using the linear increase form (Fig. 35A), the coefficient is 166,000 psi per 1% carbon in the unalloyed steels and from 337,100 to 428,300 psi for two different alloyed systems — Figs. 34 and 36.

At the same time, carbon additions degrade impact properties as a power function of carbon content. This is illustrated by the Figs. 37 and 38 log-log scale plots for argon-oxygen shielded metal-arc welds. These welds were nominally unalloyed, except for the fact that some of them contained copper between 0.21 and 0.84%. At room temperature the absorbed energy values degrade as a power function of carbon content, with the highest energy values being obtained for the 0.03 to 0.06% carbon content range.

The same interrelation form exists for alloyed steel welds. All process-composition group combinations studied conform to this carbon content-energy format, except that the position of the scatter band shifts from lower to higher, depending upon the remainder of the alloy make-up. In no case was the maximum break-off point from the 240 ft-lb plateau higher than 0.14%, and this was for the high purity 4.5%Ni–2%Mo content series of Fig. 19.

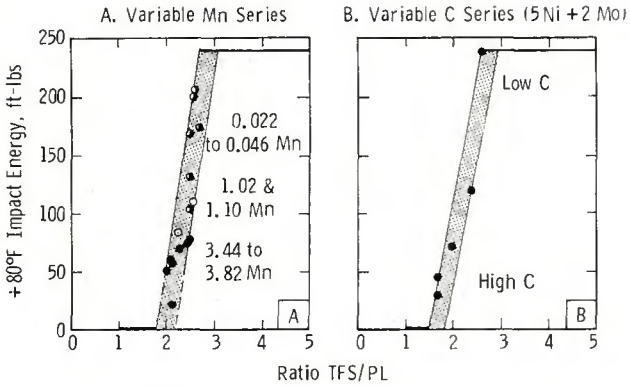

Fig. 29 — Dependence of impact energy values upon ratio of T.F.S. to P.L. for gas tungsten-arc welds

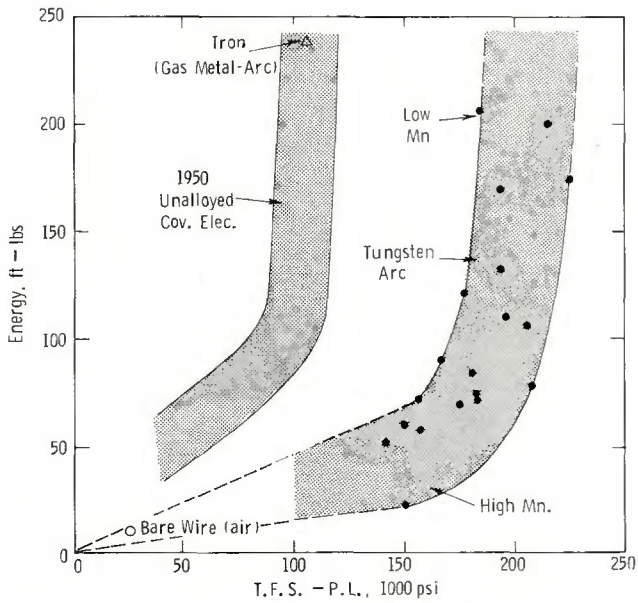

Fig. 31 — Impact energy dependence on (T.F.S. – P.L.)

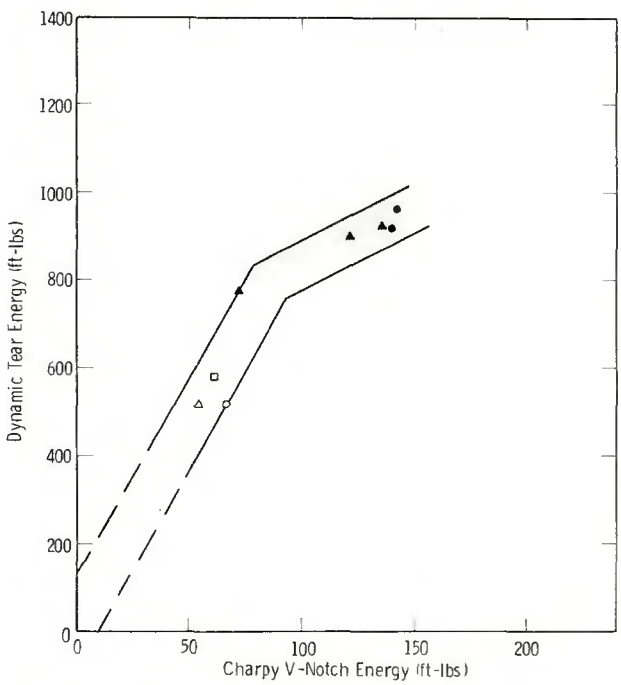

Fig. 33 — Relations between dynamic tear and Charpy V-notch energies for gas-shielded arc welds

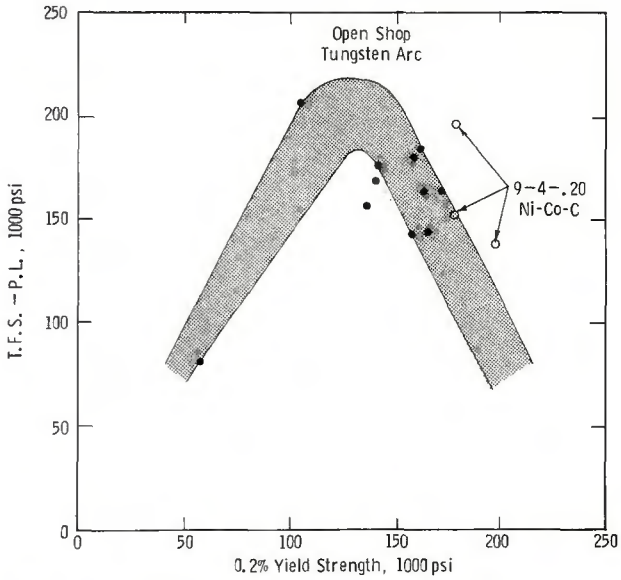

Fig. 30 — Relation between (T.F.S. – P. L.) and yield strength

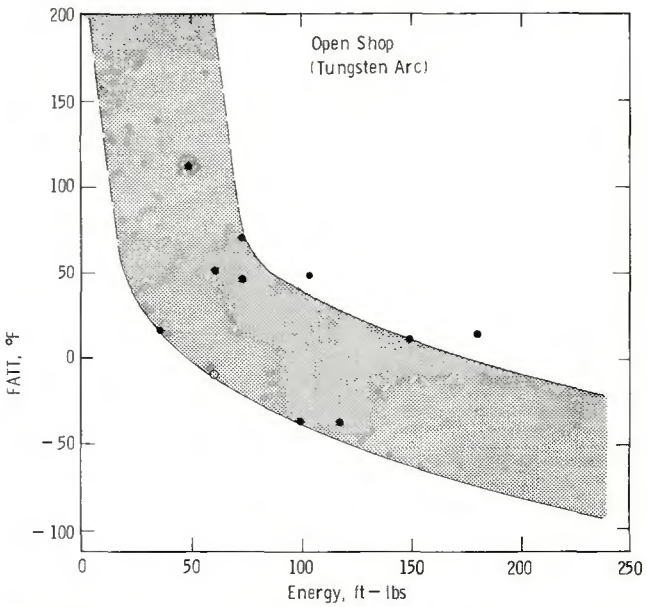

Fig. 32 — Relations between impact energy at + 80 F and FATT values

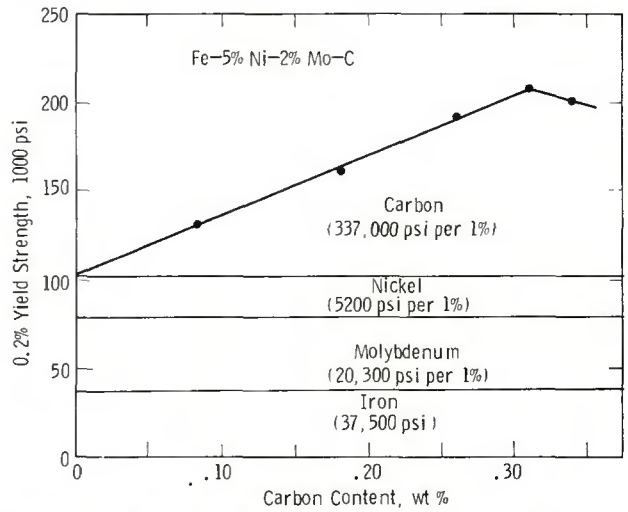

Fig. 34 — Composition dependence of yield strength for Fe-5% Ni-2% Mo-C steel welds

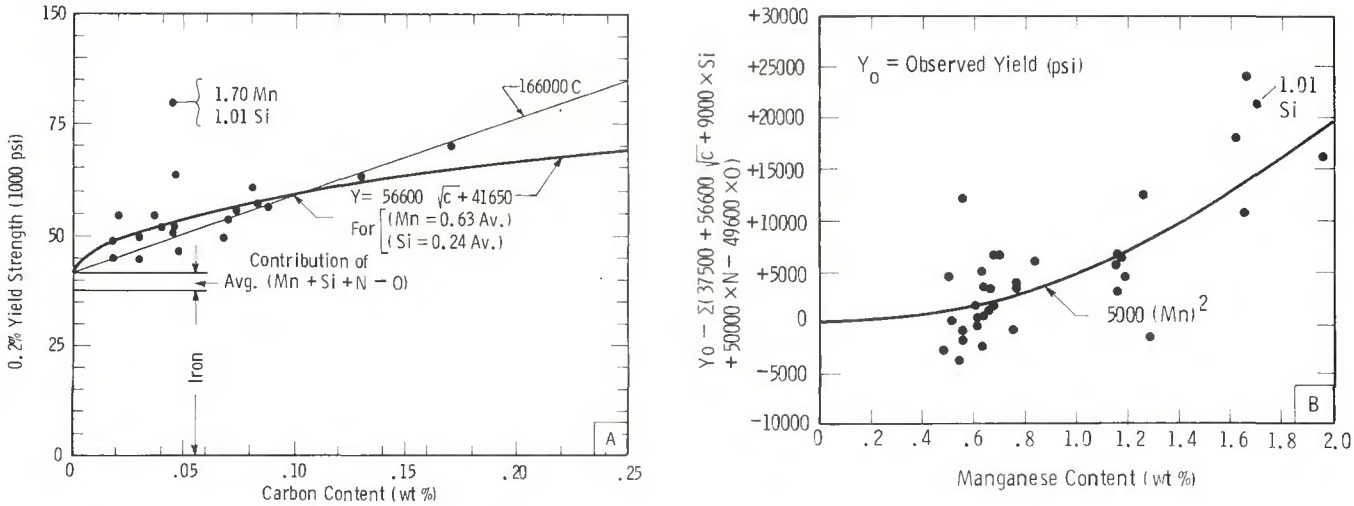

Fig. 35 — Influence of C and Mn on 0.2% yield strengths of carbon steel argon shielded metal-arc weld metals made with lightly coated electrodes

The effect of carbon upon mechanical properties, therefore, immediately clarifies the reasons for the upper strength-toughness barrier. To obtain higher tensile strengths, more carbon is desirable. Such additions only gradually increase the strength, whereas they drastically decrease the energy absorbed.

Manganese

The role of manganese upon weld mechanical properties is somewhat contradictory. The first known attempt to verify the benefit obtained by the complete removal of manganese from the weld deposit on the impact properties was made in 1962 — Fig. 39.[24,25] The 152,300 psi yield strength weld having the tensile and impact properties shown, had a TFS:PL ratio of 2.56:1.00, and an impact energy value of 200 ft-lb at +80 F.

Minimization of manganese content (less than 0.05%) results in higher ratios of true stress at fracture to proportional limit, with the resultant high impact energy values — Fig. 29A. Conversely, the opposite result is obtained with manganese contents of above 3%. Such manganese additions add little to the yield strength but significantly reduce the impact energy values — Fig. 40.

In otherwise unalloyed carbon steels, manganese additions, up to 2%, tended to increase the yield strength with a second power effect. For example, in the iron-carbon-silicon-manganese series of Fig. 1, efforts to calculate the yield strength without attributing any strengthening influence to manganese resulted in the deviation shown in Fig. 35B. The deviations were eliminated by introducing a second power strengthening effect for manganese. That relation, when multiplied by a coefficient of 5000, described the increases in yield strength for 78 of the 91 unalloyed weld metals studied.

Reducing the manganese content to levels of less than 0.50%, and to as little as 0.02%, detracts little from the strength but increases the capability for energy absorption — Figs. 39 and 40. All of the ultra-tough weld metals obtained were of the nil-manganese composition type.

High 0.2% yield strengths (up to 207,000 psi) were obtained without manganese additions, but high impact energy values were never obtained when high (>1%)manganese contents were used.

Oxygen

Oxygen is a strength detractor (Fig. 41) and its increasing presence rapidly degrades weld toughness — Figs. 42 and 43. It may reduce the 0.2% yield strength at a rate of as much as 130,000 psi per 1% of oxygen present — Fig. 41. When present in very small amounts (<20 ppm), as desired for good impact toughness, its presence has no influence upon weld strength.

Unalloyed carbon steel covered electrode welds, which may have oxygen contents from 0.033 to 0.110%, can have their yield strength lowered by as much as 14,000 psi as the oxygen content increases. However, not all of this change in yield strength is necessarily the consequence of the change in oxygen levels. The lower levels of oxygen contents are obtained when the C, Mn, and Si contents are higher, and those three elements are all weld strengtheners. At the opposite extreme, the high oxygen content welds are usually low in C, Mn, and Si contents. Such welds are necessarily lower in strength, but the lower strength does not always result from the high oxygen content. The lower yield strengths can be beneficial when welding the low strength anisotropic carbon steels.

In the cases described, the true stress at fracture decreases much more rapidly than the yield strength — Fig. 41. Since the values of true stress at fracture and impact toughness are related, it is expected that oxygen would have a deleterious effect upon impact properties. This is shown in Fig. 42 for covered electrode weld metals as produced with the alloy steel electrodes available in 1960. Another illustration of the degrading effect of oxygen upon weld impact toughness is provided by the flux-cored electrode, CO_2-shielded, metal-arc welds — Fig. 43. The higher (0.124%) oxygen content weld had an impact energy value of 28 ft-lb, whereas the normal level for lower (0.037 to 0.054%) oxygen content welds was from 44 to 76 ft-lb.

Both low and high yield strength welds were produced with the higher oxygen levels, but high impact energy values were obtained only when the oxygen contents were low (<20 ppm).[29,30]

Nitrogen

Nitrogen tends to increase the yield strength at a rate of approximately 50,000 psi per 1% of nitrogen in the weld deposit. However, since the nitrogen contents of modern welds a e very low, usually less than 0.010%, nitrogen has no significant influence upon weld strength. Even in deposits which contained as much as 0.10% nitrogen, the maximum contribution to the yield strength was only about 5000 psi.

At the same time, the added nitrogen rapidly degrades the impact energy values. A summary of the impact results obtained for the 91 unalloyed carbon steel welds tested, for the several processes, is shown in Fig. 44.

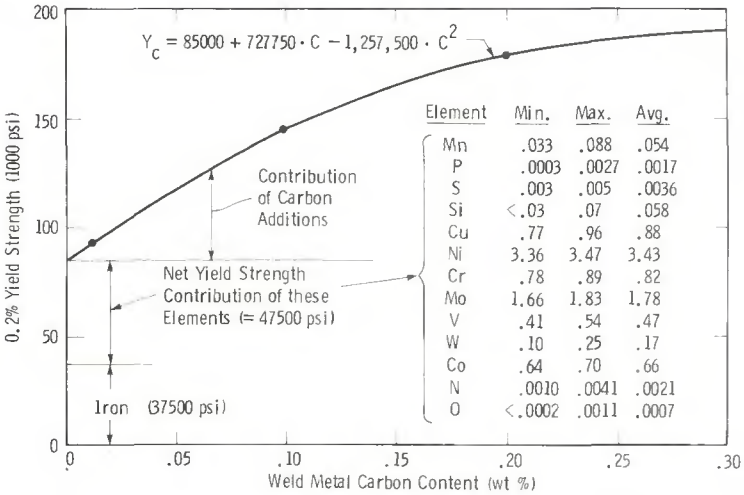

Fig. 36 — Illustration of second power binomial effect of carbon on yield strength

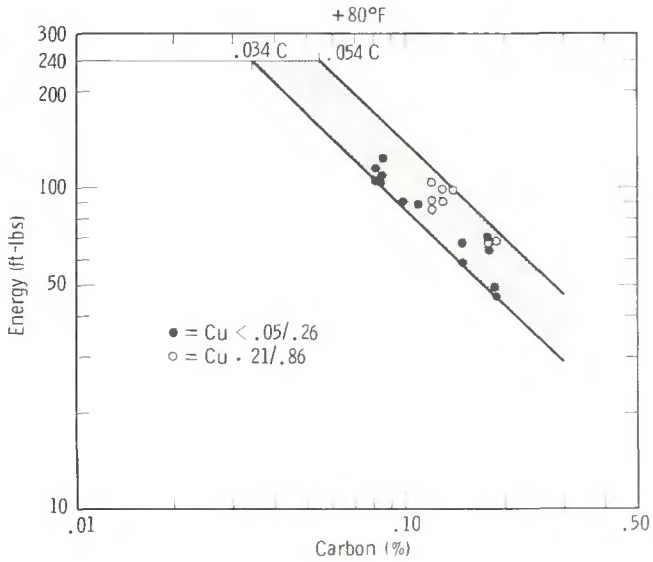

Fig. 37 — Influence of carbon and copper on toughness of 99% Ar-1% O_2 shielded metal-arc welds (Mn .52/1.58; Si .32/.94; N < .0093; O = .010/.044)

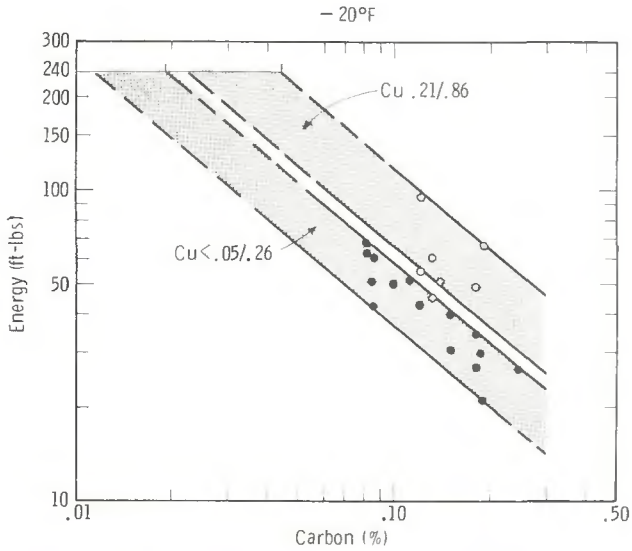

Fig. 38 — Influence of carbon and copper on toughness of 99% Ar-1% O_2 shielded metal-arc welds (Mn .52/1.58; Si .32/.04; N <.0093; O = .010/.044)

Nitrogen is not the only variable in the summary shown, but it is an important factor.

The near elimination of nitrogen tends to produce welds of maximum soundness and toughness, with minimum reductions in their strength.

Phosphorus

The influence of phosphorus on weld properties was studied up to levels of 0.16% in the deposits. At that level, the resulting welds were brittle even for idealized gas tungsten-arc welding conditions, within the sealed chamber of pure argon. The best total tensile elongation value obtained for phosphorus levels of 0.06 to 0.16% was 1.9%.

Impact energy values of such welds ranged from 7 to 44 ft-lb at room temperature for welds having 0.2% yield strengths between 126,000 and 145,000 psi. The true stress at fracture for these high phosphorus content welds ranged from 167,000 to 198,400 psi, with the TFS-PL differences ranging from 55,000 to 75,200 psi. All the strength, ductility, and toughness indexes indicate the advisability of maintaining phosphorus at low levels, preferably less than 0.010%.

Sulfur

Before the beginning of the described experiments, it was established that sulfur contents should be low. Accordingly, no new test data are provided by these studies. The sulfur contents of all experimental filler metal compositions studied were less than 0.011%. The highest observed sulfur content in welds made with commercial electrodes (covered and flux cored) was 0.030%.

Silicon

Silicon was found to increase weld yield strength for both the carbon and the alloy steel compositions (about 9000 psi per 1% Si). It decreased toughness — Fig. 23. Accordingly, most of the compositions studied, exclusive of the covered electrode and submerged arc welds, were relatively free of silicon. Silicon is added to the weld metal in those two processes from the molten fluxes, and even welds made with silicon-free filler metals and base metals contain significant levels of silicon.[1]

Welds having 0.2% yield strengths up to 207,000 psi were made without the need for silicon additions. Maintaining this element to low levels, therefore, presents no particular hardship, particularly for the gas shielded arc processes.

Copper

Copper additions to either the body or the surfaces of mild steel electrodes such that the weld deposits contain between 0.21 and 0.86% copper improved both the impact energy

levels and the yield strengths — Figs. 37, 38, and 10. At the same time, these copper additions tend to depress the FATT values. Thus, copper, added to the carbon steel system, is a useful alloying agent, except when its presence may increase the already too high yield strength of the weld metals to the level where they become over-strong and thus increase the susceptibility of base metal cracking — Fig. 3.

For alloy steel systems, the addition of copper in the deposits, up to 1.0 or 1.5%, is beneficial. All five of the welds in Fig. 45 which have true stress at fracture values of more than 300,000 psi and do not contain Al or Cb contain between 0.63 and 3.91% copper. The Fig. 39 weld contained 0.89% copper. Some of the Fig. 18 series of welds contained as much as 2.06% copper, although many of these were copper-free. Further additions of copper, up to 4.9%, added little to the yield strength and detracted rapidly from the impact energy values.

Nickel

Additions of nickel, up to 10%, provide increased strength and toughness — Fig. 30. Nickel is not a powerful strengthening agent; it increases the 0.2% yield strength at a rate of about 3000 to 8000 psi per 1% of nickel present, depending upon the amount of other elements already in the alloy.

Nickel retards the rate of degradation of impact toughness. Toughness at low temperatures is particularly improved by nickel additions, provided the O, N, S, P, Mn, and Si levels are low. The Fig. 39 weld contained 3.41% nickel. Strong and tough welds were made when using a 4.5%Ni-2%Mo alloy — Figs. 19 and 26.[26]

Chromium

A specific instance where one element — chromium — first increases and then decreases the yield strength was shown in Fig. 12. Those welds were made with commercial covered electrodes. As the chromium content increased from zero — that is, a mild steel weld — to about 4–6%, the yield strength increased. Further additions, up to about 12%, decreased the yield strength. Additional increases of chromium had no significant effect upon strength.

The Fig. 12 series also provides an illustration of the effect of an individual element upon the difference between the true stress at fracture and the proportional limit. That differential was increased as the chromium content was raised from 0 to 5% — Fig. 46. Further chromium additions decreased the strength differential. This relationship can be expressed mathematically by using the equation for the N-leaved rose, or for the pos-

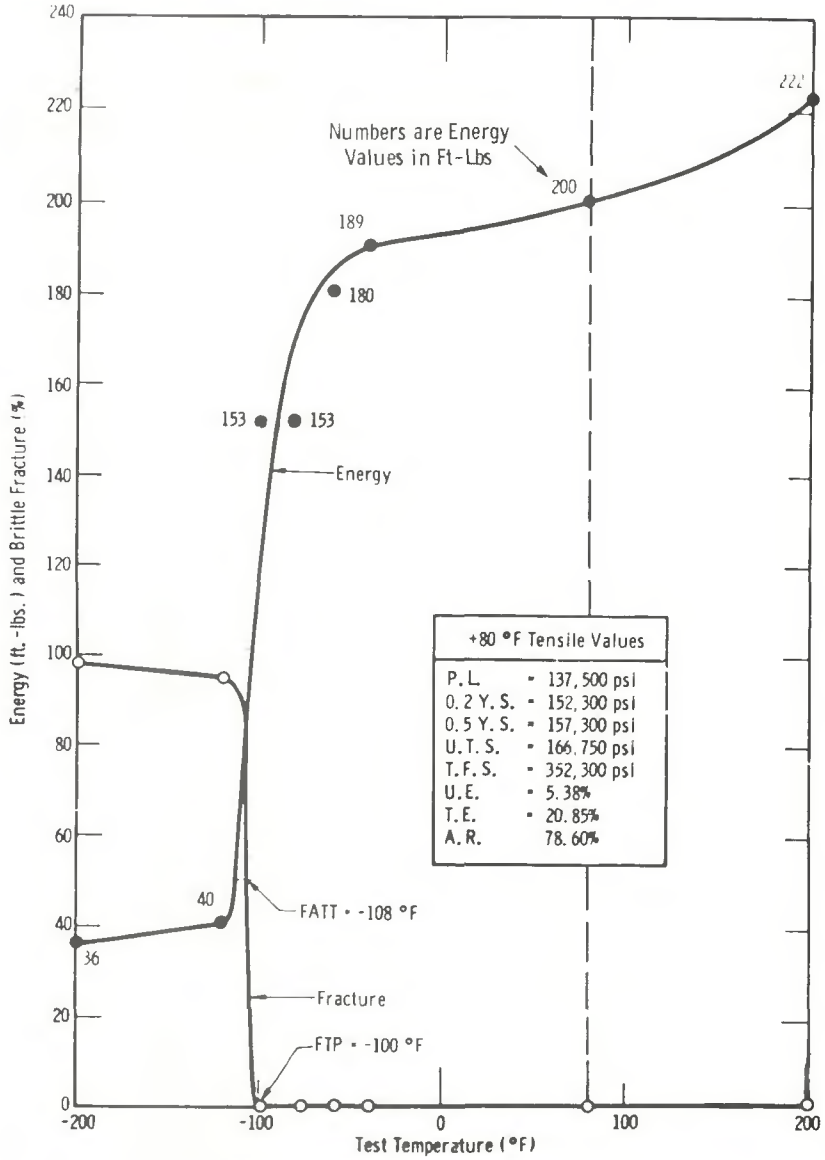

Fig. 39 — Temperature dependence of high-purity gas tungsten-arc weld metal impact properties

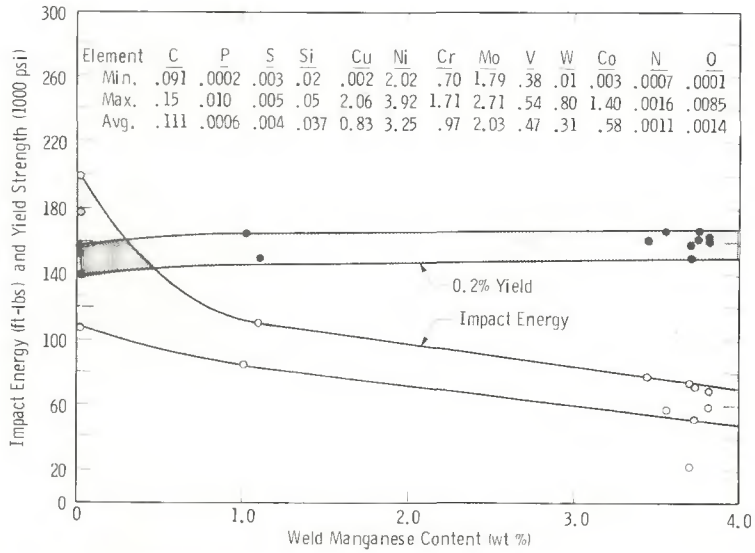

Fig. 40 — Manganese dependence of alloyed steel gas tungsten-arc weld properties

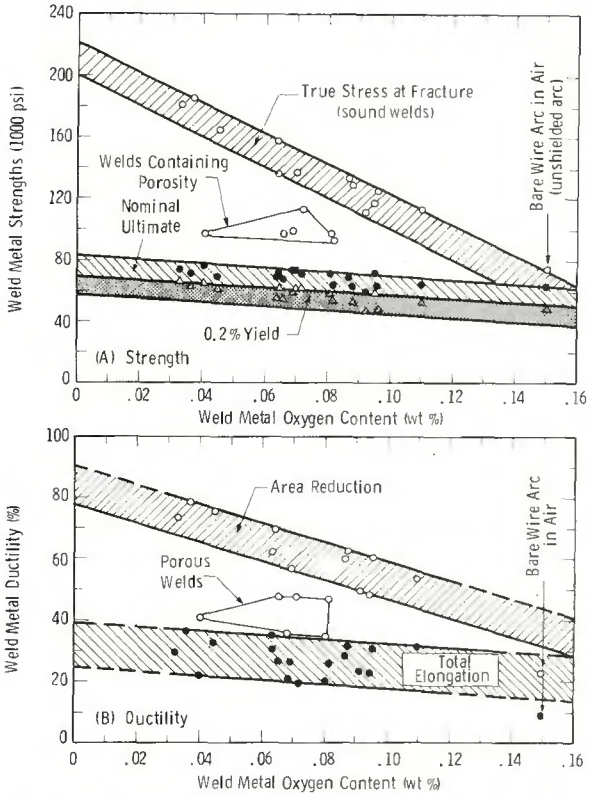

Fig. 41 — Oxygen dependence of tensile properties of covered electrode unalloyed steel weld metals (C .05/.10; Mn .25/.78; Si .06/.60; N .006/.043)

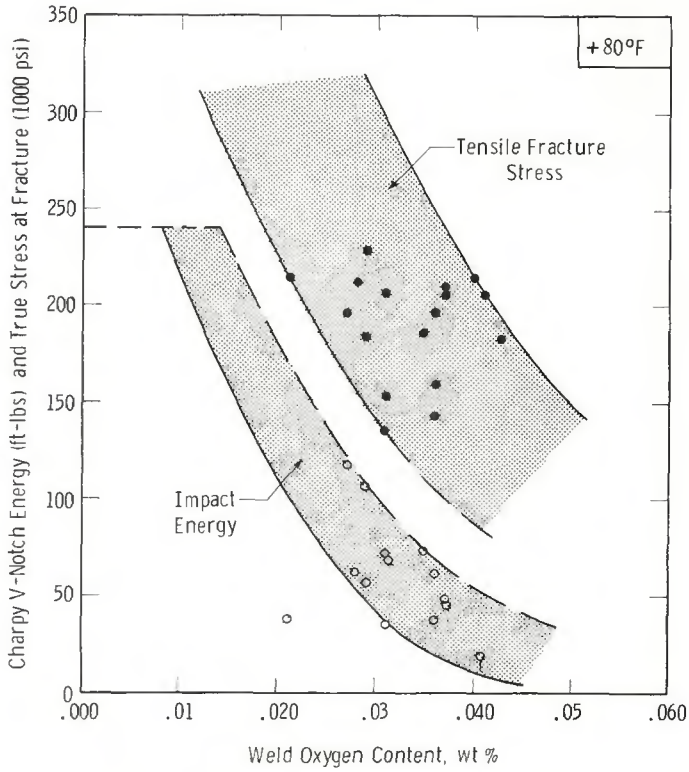

Fig. 42 — Dependence of impact energy and tensile fracture strength upon oxygen content (1960 vintage covered electrodes)

itive quadrant portion of the folium of Decartes.

Chromium was used in experimental alloy combinations of up to 4.29%. It added about 9500 psi to the yield strength per 1% of chromium present in the weld, without detracting too significantly from the toughness values. Weld metals having yield strengths of 40,000 to 207,000 psi were produced without chromium additions. Some of these chromium-free welds were the toughest made. All of the best impact toughness values were obtained from welds containing less than 1.0% chromium.

Molybdenum

The effect of molybdenum contents was studied up to 5%. Molybdenum, which increases the yield strength at a rate of about 20,000 psi per 1% present, is a more potent unit strengthening agent than manganese, silicon, nickel, or chromium.

Maximum toughness welds, up to 240 ft-lb, were obtained with molybdenum contents up to 2.25%. The presence of more than 2.25%Mo degraded toughness. The potential for obtaining up to a 45,000 psi increase in yield strength (20,000 x 2.25), without significant degradation in impact toughness, makes it an attractive alloying element. As for all other elements, the presence, or absence, of molybdenum does not assure that the welds will be tough; the other elements must be present in proper amounts, which means that, in some cases, they are essentially absent.

The molybdenum content of the Fig. 39 weld was 1.77%. The average molybdenum content of the welds in Figs. 19, 26, and 40 was 2.03%. The optimum level for molybdenum is about 2.0%.

Vanadium

Vanadium can be a potent strengthening element, but in some combinations it adds little to, and can even detract from, the strength. When large (1.6 to 2.1%) amounts of vanadium were added to nominally unalloyed carbon steel, the yield strength was lowered. In these two cases, the impact values were excellent (238 ft-lb) between room temperature and +200 F, but poor at all lower temperatures.

The high toughness-high strength, Fig. 39 weld contained 0.48% vanadium. For the various alloy combinations studied, the higher impact toughness values were obtained only when the vanadium content was maintained to levels less than 0.50%, and preferably less than 0.15%. Higher amounts rapidly degraded the impact energy values, particularly at the lower test temperatures. This was true even in the absence of significant levels of oxygen.

Tungsten

While tungsten is another weld strengthener, test data are available only up to 0.8%. Maximum toughness weld impact energy values were obtained only up to levels of 0.20%W; higher amounts degraded the energy values at all test temperatures.

Cobalt

Cobalt increases the yield strength at the rate of about 5000 psi per 1%. It was studied in amounts up to 3% in the series being reported and is being successfully used commercially in amounts up to about 6% — Fig. 30.

Maximum toughness welds were obtained with cobalt contents only as high as 0.85%; higher amounts caused degradation of the impact energy values. The Fig. 39 weld contained 0.68% cobalt.

Aluminum

In the carbon steel series, small (<0.06%) amounts of aluminum additions increased all strength values, but decreased the ductility and toughness. For best results, the soluble aluminum should be less than 0.02%, and the insoluble (Al_2O_3) should be less than 0.012%.

In the alloy steels, aluminum additions in small amounts (0.22%), and in the absence of nitrogen, were a mildly effective strengthener and

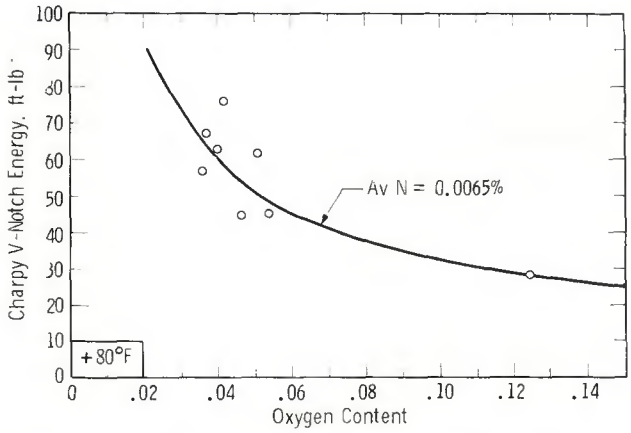

Fig. 43 — Oxygen dependence of Charpy V-notch energy values for CO_2 shielded flux cored weld metals

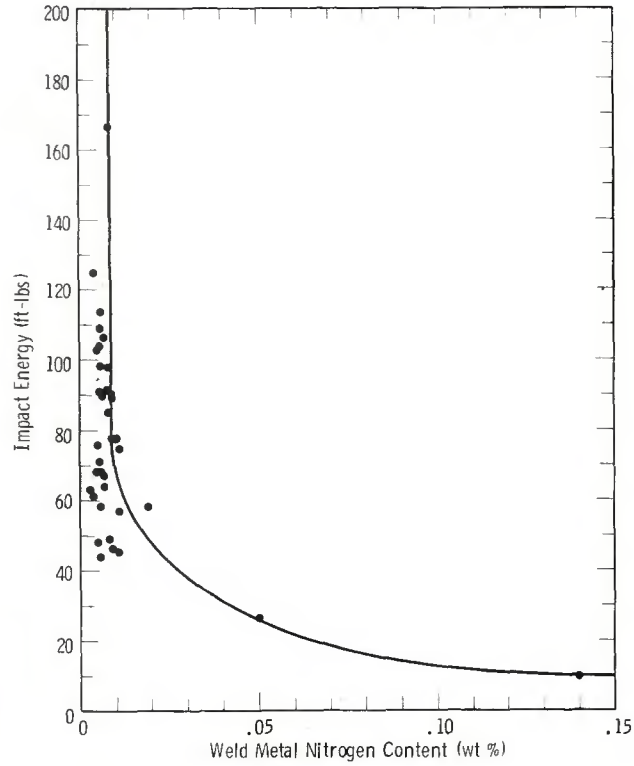

Fig. 44 — Nitrogen dependence of Charpy V-notch impact values at +80 F for unalloyed carbon steel weld metals (all processes)

tended to improve the impact values, possibly via the grain refinement route. The true stress at fracture remained high (TFS = 338,000 psi; TFS – PL = 192,600 psi), Fig. 45, and the impact energy value at +80 F was 132 ft-lb for a 164,200 psi yield strength weld metal.

Columbium

The presence of columbium up to 1.19% was effective as a strengthener (Fig. 45), but the resulting impact energy values were low (6 to 55 ft-lb). Best results were obtained when no columbium was present.

Titanium and Zirconium

Titanium contents up to 0.63% and zirconium contents up to 0.78% were effective as strengtheners (Fig. 45), but their use resulted in low impact energy values (4 to 44 ft-lb). Best results were obtained when no titanium or zirconium were present.

Summary

Strength-Ductility-Toughness Ranges

1. The knowledge, and the technology, exists for producing 0.2% tensile yield strength, multipass, as-deposited, ferritic steel, weld metals anywhere within the 37,000 to 207,000 psi range, when loaded at a constant strain rate of 750% per hour at room temperature — Fig. 2

2. The ductilities of such welds tend to decrease with increased strengths — Fig. 2.

3. Welds of improper compositional make-up have ductilities so low that rupture occurs under rising load conditions. Such welds are low impact energy absorbers.

4. Charpy V-notch energy values up to 240 ft-lb can be obtained at room temperature. The obtained energy values tend to degrade with increased yield strength (Figs. 20-26) — that is, with higher weld composition levels. The high yield strength welds have the lower true stress at fracture to proportional limit ratios — Fig. 27.

Tensile Strengths

1. The proportional limit and ultimate strengths for sound, ductile welds tend to increase with the yield strength.

2. The true stress at fracture, for any progressively enriched alloy series, first increases more rapidly than the yield strength and then less rapidly — Figs. 1 and 11. This produces both a variable ratio and differential between true stress at fracture and proportional limit values — Figs. 27 and 30.

3. The tensile test specimen should be more effectively and widely used. The magnitudes of uniform elongation and of the breaking load should always be observed and recorded. The first value categorizes the work hardening potentials. The second value provides the base for calculating the true stress at fracture.

4. The differential between true stress at fracture (final breaking load divided by final cross-section area) and the proportional limit stress largely determines the impact toughness of a weld — Figs. 28, 29, and 31. This differential is usually a maximum at an intermediate strength level, for any progressively enriched alloy system — Fig. 30.

Plate Anisotropy Related to Weld Strength

Steels being welded are often not isotropic — Figs. 3 and 4, and Table 1. Corrective courses of action available are:

1. Users should cooperate with the steel producers, but insist that the through-thickness fracture strengths, ductilities, and toughness of steels be improved to meet reasonable minimum levels, particularly for those designs which involve the use of corner and tee joints.[2]

2. Reduce the strengths of the welds being used, particularly for the carbon steels. The yield strength of the weld metals should not be more than 15% above that of the base metal being welded.

3. Present weld metal specifications should be modified to provide for a 45,000 psi maximum yield strength grade weld metal for welding the low strength, anisotropic carbon steels. The use of low weld metal yield strengths tends to provide welds of maximum ductility, minimum residual stresses, and minimum susceptibility to weld and plate cracking.

4. Improve designs to minimize application of through-thickness residual stresses.

5. Employ assembly procedures and welding sequences which minimize the magnitudes of residual stresses.

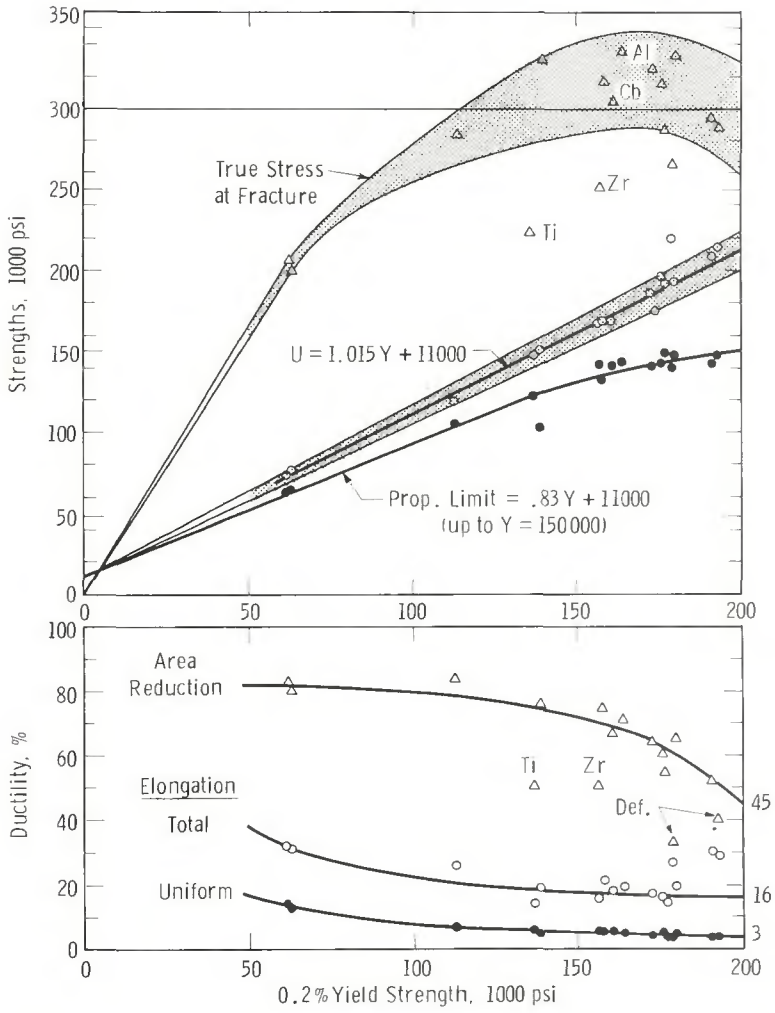

Fig. 45 — Tensile properties of dry-box gas tungsten-arc welds with copper bearing high-purity alloy steel filler metals

Impact Properties

1. The energy absorbed in the impact test increases with increases in the ratio of and the differential between the magnitudes of the true stress at fracture and the proportional limit stress — Figs. 28–31. When this ratio or differential reaches a maximum, the impact energy values achieve their maximum. As alloy contents are further increased, and the ratio of and differential between true fracture stress and proportional limit stress decreases, the impact energy absorbed decreases.

2. Fracture appearance transition temperatures of alloy steel weld metals are raised by those factors which decrease impact energy absorption, and vice versa — Fig. 32.

3. The limitation in obtaining higher impact energy values for the higher yield strength steel weld metals lies in the fact that the true tensile stress at fracture for those compositions does not continue to increase with increased values of the proportional limit and yield strengths — Figs. 1 and 11. Convergence of the true tensile stress at fracture and the proportional limit values (Fig. 1), as a consequence of alloy additions, results in tensile and impact brittleness in a manner similar to that which occurs as temperatures are decreased — Figs. 8 and 39.

Composition Dependence of Strength and Toughness

1. Weld strengths increase progressively with increased alloy additions, up to some level. Further alloying additions tend to decrease the rate of increase of strengths. These strength-composition relations can be expressed algebraically.

2. Most alloying additions, including carbon, manganese, chromium, and other elements, above a describable level, decrease impact energy absorption values more rapidly than they increase strength. Accordingly, as strength increases, above a particular level, toughness decreases.

3. Toughness is improved more by the omission of certain elements than by the addition of other elements. The near complete elimination of O, N, P, S, Mn, Si, etc., improves toughness and suppresses the FATT values.

4. Each element has its individual effect:

Carbon — *increases* the 0.2% yield strength, on the whole, as a linear function (Fig. 34) but may also contribute as a square root function (Fig. 35A) or as a binomial function of carbon content (Fig. 36), but in all cases *decreases* the impact energy absorption capacity as a power function of added carbon content — Figs. 37 and 38. This illustrates the basic reason for the upper strength-toughness barrier.

Manganese — *increases* yield strength by a first or second power factor, but *decreases* impact energy values — Figs. 35B and 40.

Phosphorus — *decreases* strength *and* toughness.

Sulfur — *decreases* strength *and* toughness.

Silicon — *increases* strength but *decreases* toughness.

Copper — *increases* both strength and toughness (up to about 1.5%).

Nickel — *increases* both strength and toughness.

Chromium — *increases* strength up to about 6%, Fig. 12, but more than 1% *detracts* from toughness.

Molybdenum — *increases* strength up to about 2.25%, but more than 2.25% *decreases* impact toughness.

Vanadium — *increases* strength but *decreases* toughness when more than 0.15% is used. When used alone in carbon steels, up to 2.0% vanadium does not increase strength.

Tungsten — *increases* strength, but *decreases* toughness.

Cobalt — *increases* both strength and toughness.

Aluminum — *increases* strength up to 0.06%, but more than 0.015% *decreases* toughness.

Columbium — *increases* strength but drastically *decreases* toughness.

Titanium — *increases* strength but drastically *decreases* toughness.

Zirconium — *increases* strength but drastically *decreases* toughness.

Nitrogen — *increases* strength but drastically *decreases* toughness.

Oxygen — *decreases* both strength and toughness — Figs. 41-43. The presence of more than 0.05 wt-% (500 ppm) may obscure FATT values by causing grain boundary failures.

5. For unalloyed carbon steels, at normal heat inputs, the 0.2% yield strength of multipass, as-deposited weld metal may be calculated as:

$$Y_c = 37{,}500 + 57{,}400\sqrt{C} + 5000(Mn)^2 + 9000\,Si + 50{,}000\,N - 50{,}000(O).$$

6. The complexities of the many interdependent relationships between the several elements on strength and toughness prevent publi-

cation of corresponding equations for the alloy steel welds at this time.

7. Preferred alloy weld compositions, for maximum strength *and* toughness, involve combinations of (Fe + C) + (Ni, Mo, Cu, and Co), with very low P, S, N, O, Mn, Si, Al, Cb, Ti, and Zr contents.

8. Useful alloying elements include Cr, V, W, and Ta.

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Electrode coatings were applied at the Montevallo Plant. In-chamber welds were made at the Cheswick and Astronuclear sites. Dynamic tear energy test data were furnished by L. Mayr and W. J. Erichsen, Sunnyvale Plant.

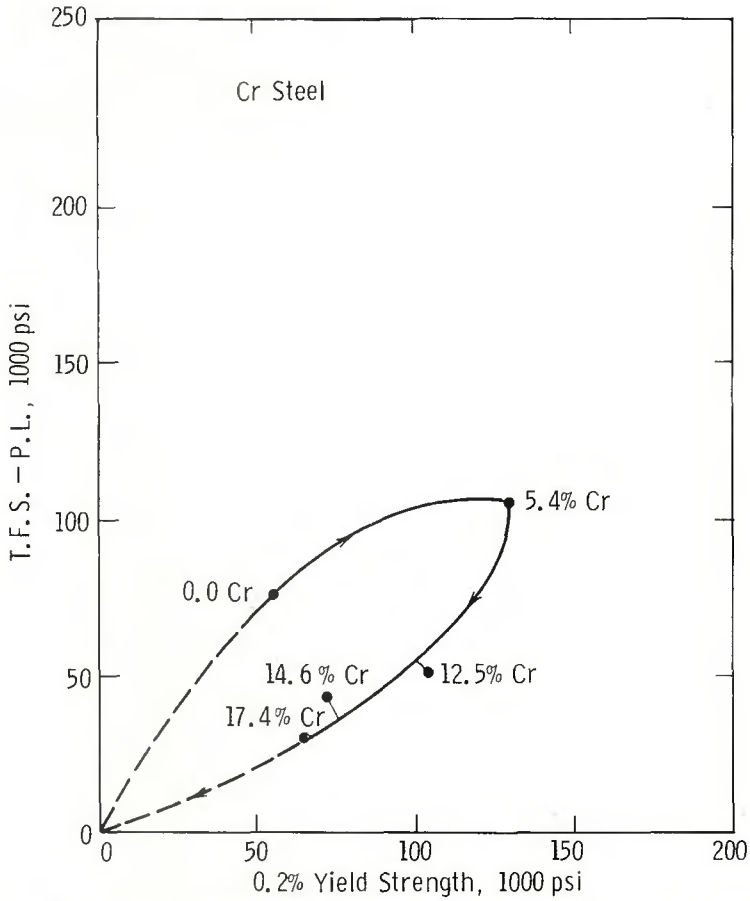

Fig. 46 — Relation of T.F.S. - P.L. and yield strength for Cr steel weld metals (covered electrodes)

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