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FINAL REPORT

THE INFLUENCE OF WELD METAL ALLOYING ADDITIONS TO EXTEND THE HEAT INPUT RANGE FOR THE SUBMERGED ARC WELDING OF HIGH STRENGTH STEELS

(Work performed under contract N00014-90-J-1889)

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DECEMBER 16, 1993

CENTER FOR WELDING AND JOINING RESEARCH

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Weld metal microstructural development for high strength steels when welded with submerged arc welding process was investigated as a function of consumable composition and thermal experience. Of specific interest is the effect of systematic variations of microalloying additions on broadening of applicable heat input range. Controlled weld metal oxygen content, particularly in the range of 300 to 400 ppm, has been found to improve HY-130 steel weld metal toughness. Molybdenum additions was found to increase the strength of the HY-130 steel weld deposits. Copper additions up to 3.5 wt.pct. were found to strengthen the high strength steel weld metals, in particular, those of higher heat input, 3.6 kJ/mm. Niobium additions alone did not provide as powerful strengthening effect in the high heat input weld metals as the copper additions. In the case of copper-enriched welds, multi-pass welding induced both the precipitation and overaging of ε-copper precipitates in the reheated weld metal which resulted in non-uniform mechanical properties. When added together, copper and niobium produced the synergistic effect of dual precipitation (ε-copper and niobium carbides) which provided the needed strength and thermal stability to the reheated weld metal even at high heat inputs. With this novel approach, the applicable heat input range to produce both adequate weld metal strength and toughness in high strength steels ($\sigma_y > 690$ MPa) can be extended significantly. The optimal additions for copper and niobium were found to be 3.3 and up to 0.1 wt. pct., respectively.

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ABSTRACT

Weld metal microstructural development for high strength steels when welded with submerged arc welding process was investigated as a function of consumable composition and thermal experience. Of specific interest is the influence of systematic variations of microalloying additions on weld metal microstructure. The additions were made to two commercially available HY-130 steel welding consumables. The effectiveness of non-metallic inclusions, precipitates, and other additions on extending the applicable heat input range in producing both adequate weld metal strength and toughness was examined. HY-130 steel, with approximately 900 MPa yield strength, has been used as a prototype in this research program. However, the study developed and the results obtained are applicable to other high strength steels such as the HY-100 steels.

Controlled weld metal oxygen content, particularly in the range of 300 to 400 ppm, has been found to improve HY-130 steel weld metal toughness. Specific weld metal inclusion types, concentration and size distribution were necessary to obtain optimal toughness. Oxygen content above 400 ppm resulted in significant oxidation of the alloying additions which also reduced weld metal strength. Molybdenum additions was found to increase the strength of the HY-130 steel weld deposits. However, excessive amounts of molybdenum is not advised since its presence in high concentration may increase the susceptibility of the weld metal to cracking.

Copper additions were found to strengthen the high strength steel weld metals. In particular, welds of higher heat input, 3.6 kJ/mm, were observed to benefit more from ε-copper precipitation strengthening. An estimated yield strength of 900 MPa (130 ksi) can be achieved during single pass welding, with approximately 2.8 wt. pct. of copper addition. On the other hand, depositing weld beads over the copper-enhanced weld metals has resulted in non-uniform hardness in the reheated weld metal. The multi-pass thermal cycles induce the precipitation of ε-copper in some regions and the overaging of existing ε-copper in other regions, resulting in the non-uniform mechanical properties observed. Thus, the successful broadening of heat input range for single pass welding must be reconciled with the mechanical properties impairment observed in the multi-pass welds to avoid large variations in properties across the weld deposits in heavy section welding.

Niobium additions alone did not provide as powerful strengthening effect in the high heat input weld metals as the copper additions. Dual precipitation, ε-copper and niobium carbides, was observed to provide the needed strength and thermal stability even at high heat input and multi-pass welding conditions. With this novel approach, the permissible heat input range to produce both adequate weld metal strength and toughness in high strength steels (σ_y > 690 MPa) can be extended significantly. The optimal additions for copper and niobium were found to be 3.3 and up to 0.1 wt. pct., respectively.

INTRODUCTION

The economical utilization of high strength steels with yield strengths greater than 690 MPa (100 ksi) in structural fabrication depends on the use of high heat input welding processes, proper selection of welding consumables, and pre- and post-heat treatment procedures. A significant number of publications on the welding of high strength steels exists. However, much of these works are focused on the heat affected zone microstructure and properties (1-6); only limited literature discusses the microstructure and properties of high strength steel weld metal (7-23).

The submerged arc welding process, with deposition rates as high as 45 kg/hr (16,17), is often used in structural fabrication because of the fewer weld passes required for joining thick plates. In contrast to the successful application of submerged arc welding process to ferritic steels with yield strengths less than 690 MPa (100 ksi) in the 1 to 4 MJ/m (approximately 25 to 100 kJ/in.) heat input range (11), the welding of higher strength steels using this process does not yet consistently produce weldments with acceptable mechanical properties(11). Steels with yield strength above 690 MPa (100 ksi) in general depend on tempered martensite and/or bainite to achieve the elevated level of mechanical properties. These thermally unstable microstructures make it difficult to consistently produce weldments with acceptable combination of strength and toughness (11).

In the case of high strength steel weld metals, toughness and strength as a function of heat input can generally be represented by the schematic diagram illustrated in Figure 1. At lower heat inputs where the cooling rates are high, the resulting untempered martensite achieves strength values above the minimum criteria of acceptance, but the weld metal has unacceptable toughness. At high heat inputs, the high strength steel weld metal will produce acceptable toughness but poor strength. The heat input range where both acceptable weld metal toughness and strength can be achieved is very limited. Consequently, the objective of this research program was to determine fundamental alternatives to broaden this heat input range.

To extend the usable heat input ranges for submerged arc welding of high strength steels, better understanding of the influence of heat input and weld metal composition on the microstructure and properties of high strength steel weld metal must be achieved. The approach adopted in this research, a combination of quantitative characterization of the weld metal, both microstructures and mechanical properties, and fundamental interpretation of phase transformations has broadened the applicable welding heat input range.

This investigation modified systematically commercial HY-130 steel welding consumables with oxygen, molybdenum, niobium, and copper additions, and characterized the resulting weld deposits over a broad heat input range. Each of the additions was selected to evaluate a fundamental mechanism of strengthening or toughening the high strength steel weld deposit. Two strengthening mechanisms, the transformation strengthening and precipitation hardening were considered in this program. The presence of a martensitic/bainitic matrix ensures the yield strength of a weld metal to be above 700 MPa (100 ksi), responsible for the performance necessary in the low heat input welds. For the high heat input welds (with a ferritic matrix), the precipitates provide additional strength required to match the specified properties. By designing two complementary strengthening mechanisms for the weld metal, the acceptable range of heat input was expanded for submerged arc welding of high strength steels. The effect of multi-pass welding, required in heavy section steel fabrication, on the high strength steel weld metals that contained copper-niobium additions, was also investigated.

MATERIALS AND EXPERIMENTAL PROCEDURES

The Navy Surface Warfare Center - CD supplied the 2 in. (51 mm) thick HY-130 steel plate, heat number B5365. Coupons of 150 x 50 x 25 mm (approximately 6 x 2 x 1 in) with V-grooves were used for welding with two different commercially available welding wires: (1) Airco AX-140 (heat number 51254) and (2) Linde L-TEC-140 (heat number 140005). The 1.6 mm diameter wires were produced to meet the military specification MIL-1403-1. The chemical analyses for the plate and the wires are given in Table I. Different levels of copper and niobium additions were carried out using the procedures described ahead. Specimens were extracted from the welds and prepared for microscopic examination following normal metallographic methods. The as-deposited weld metals were examined on the transverse sections after etching in 2% nital solution. Brinell hardness was measured on polished and etched specimens. Chemical analysis of the weld metals was carried out using optical emission spectrometry.

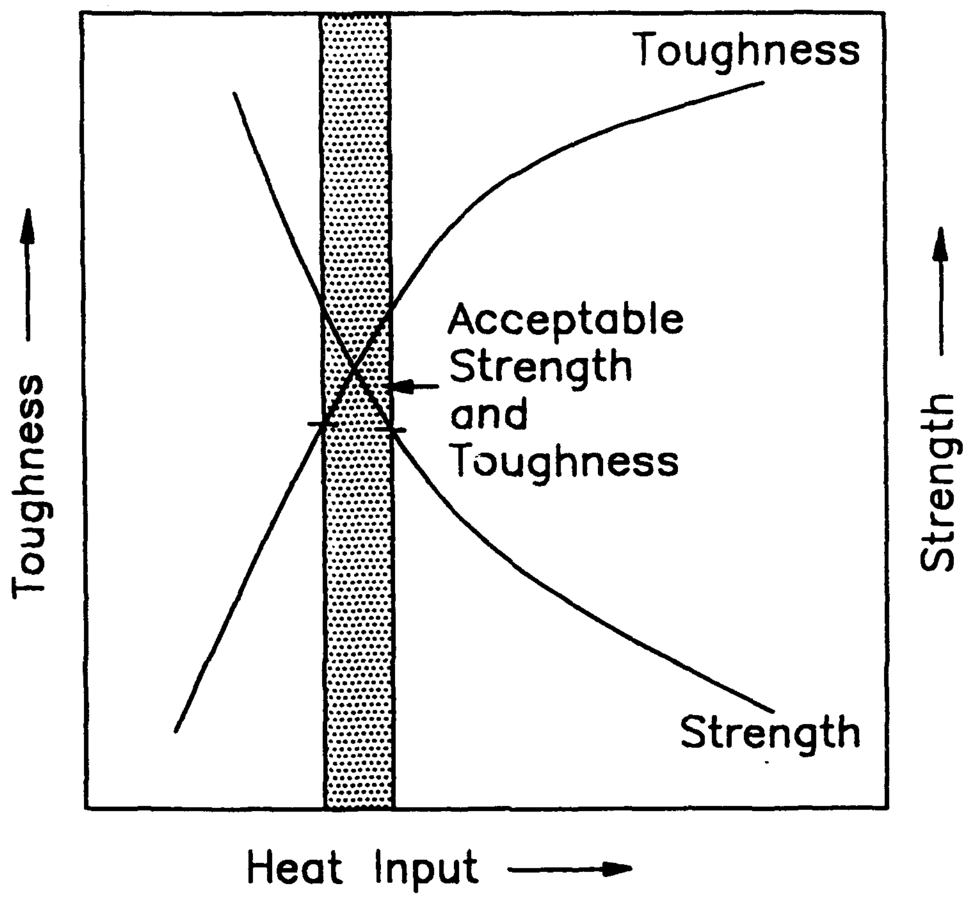


Figure 1. Schematic illustration of the opposite variation of strength and toughness in high strength steel weld metal as a function of heat input. This behavior leads to a limited range of heat inputs which allow for acceptable properties (22).

Table I. Chemical composition (in wt. pct.) of the HY-130 steel base metal and welding wires.

	C	Mn	Si	P	S	Ni	Mo	Cr	Cu
Base Metal	0.090	0.72	0.28	0.007	0.003	4.85	0.41	0.55	0.150
L-TEC 140 Electrode 1	0.076	1.55	0.39	0.004	0.002	2.47	0.80	0.73	0.031
AX-140 Electrode 2	0.093	1.71	0.24	0.006	0.004	2.10	0.63	1.02	0.047

OXYGEN-MOLYBDENUM ADDITIONS

For the determination of the effects of oxygen and molybdenum additions, submerged arc welds were made using experimental fluxes with specific additions to introduce oxygen and molybdenum. The base flux to which FeO (mill scale) and molybdenum (in the form of wires) additions were made was a commercial flux. The chemical composition of the base flux system is given in Table II.

Table II. Nominal composition (in wt. pct.) of the base flux system used in the submerged arc welding experiments. (22)

SiO_2	Al_2O_3	MgO	MnO	CaO	TiO_2	CaF2	Na_2O	Fe_2O_3	C
10.7	17.2	31.7	0.6	10.1	0.86	24.1	0.78	1.9	0.35

The submerged arc weldments were made with a Hobart MEGA-MIG 650 RVS direct current constant potential power supply with a MEGA-CON 110 microprocessor controller. The closed-looped control regulated the output voltage of the power supply and maintained the wire feed rate at programmed values. All welds were made using 350 amperes and 21.5 volts, direct current electrode positive. The welding current and potential were recorded using a two channel chart recorder.

The heat input of the welds, from 1 to 4 MJ/m, were obtained by selecting different travel speeds which allowed the welding arc behavior and metal transfer to remain fairly constant; the weld were made using a constant contact-tip-to-work distance. The HY-130 steel coupons were grit blasted to remove any paint or oxide scale and degreased prior to welding.

COPPER ADDITIONS

Efforts were made to develop a method to systematically introduce copper to the weld deposit. First copper coating were deposited onto HY-130 steel coupons using the magnetron sputtering coating system. The approach was considered because of the process capability in depositing specified coating thicknesses, which when melted during welding would introduce precise amounts of copper to the weld deposit. However, the thicknesses needed for this investigation required extensive coating periods, far beyond the practical limits of the experiment. Electrodeposition (electroplating) was attempted with no success because of adherence problems of the thick copper layers to steel.

A dual (cold wire-hot wire) wire feeder was also developed for the submerged arc welding system as schematically illustrated in Figure 2. The Type 140 grade wires were fed "hot" while the cold wire feeder introduced a "micro" copper wire into the welding arc. However, this method was discontinued

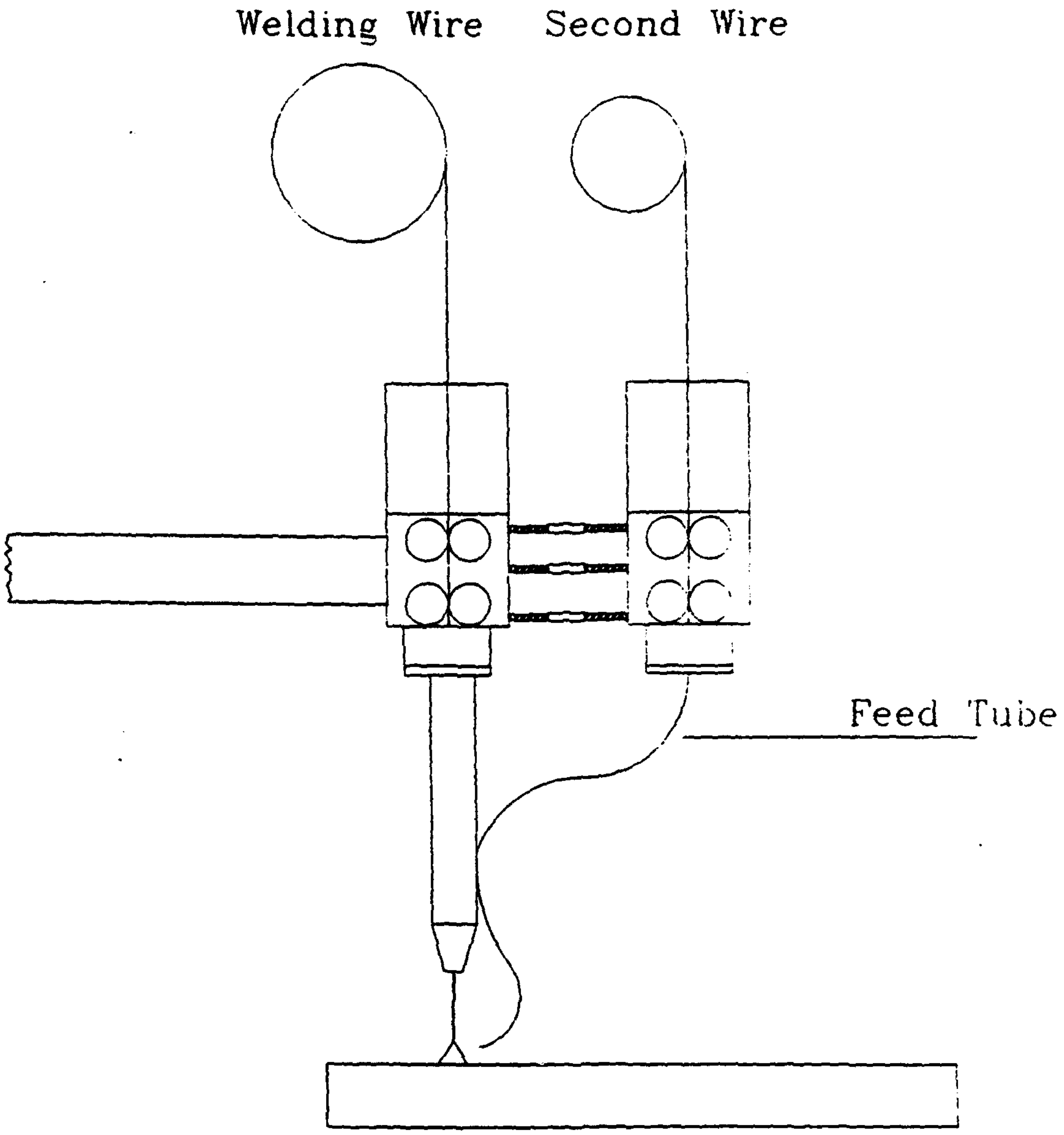


Figure 2. A dual (cold wire/hot wire) wire feeder developed for making systematic additions of microalloy elements to a submerged arc weld deposit.

because of irregular copper transfer into the weld pool and significant copper variation along the weld deposit. The non-uniform distribution of copper in the weld metal was partly responsible for the inconsistent properties observed.

Due to difficulties of introducing precise amounts of copper into the weld pool via submerged arc welding, the gas metal arc welding process, with Ar and Ar-CO_2 shielding gas, and a high purity copper (99.9 wt. pct.) welding wire of 0.5 mm (0.02 in.) diameter, was used. This procedure prepared the experimental welds via a two step sequence. First, a variable number of GTA welds to melt in a given amount of copper were made. The 6-mm deep, 80^{o}V-grooves were "buttered" using gas tungsten arc welding (190 A, 15 V, 4 ipm, and argon gas shielding). Depending on the desired copper content in the weld metal, layers of copper of different thicknesses were deposited using the variable-speed copper wire feeder. The remelting of the copper and its with the steel deposit occurred during the final pass. A higher heat input GMA weld using the Type 140 wires was then deposited to achieve proper chemical composition and mixing in the weld metal. A schematic drawing showing the experimental set up of copper additions is shown in Figure 3. The HY-130 steels coupons were grit-blasted to remove any paint or oxide scale and degreased prior to welding. The welding condition were set to result in nominal heat inputs of 1.2, 2.4, and 3.6 kJ/mm (approximately 30, 60, and 90 kJ/in.), Table III.

Table III. Welding parameters used in the experimental program.

Weld (Wire) ID	Welding Current (A)	Welding Voltage (V)	Welding Speed (ipm)	Heat Input (kJ/mm)	Wire Diameter (mm)
A (1)	280	27.3	15	1.2	1.59
B (1)	360	28.2	10	2.4	1.59
C (1)	410	29.7	8	3.6	1.59
D (1)	300	30.0	6	3.6	1.14
E (2)	410	29.7	8	3.6	1.59

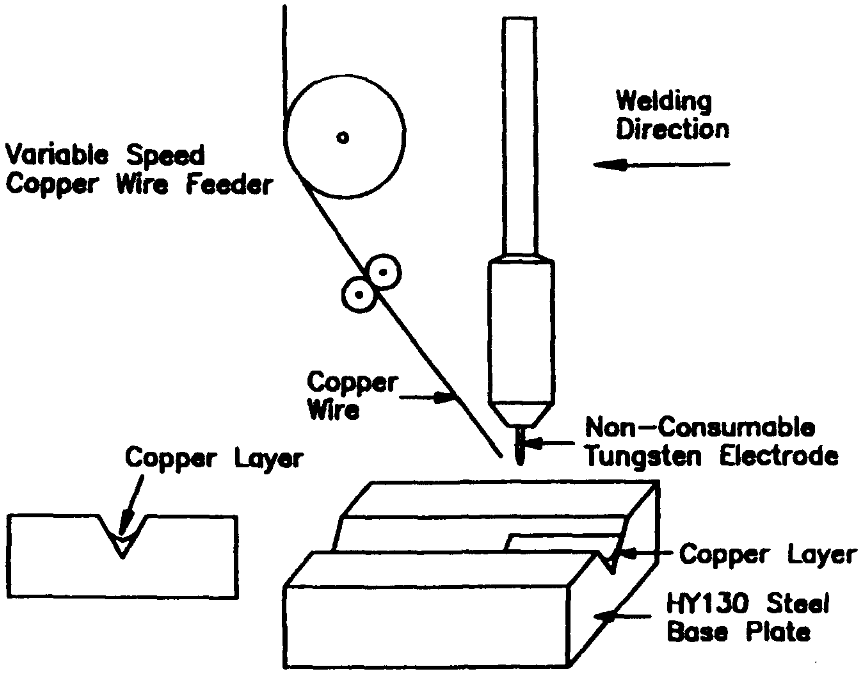
(1) Wire 1: L-TEC 140
(2) Wire 2: AX-140

NIOBIUM ADDITIONS

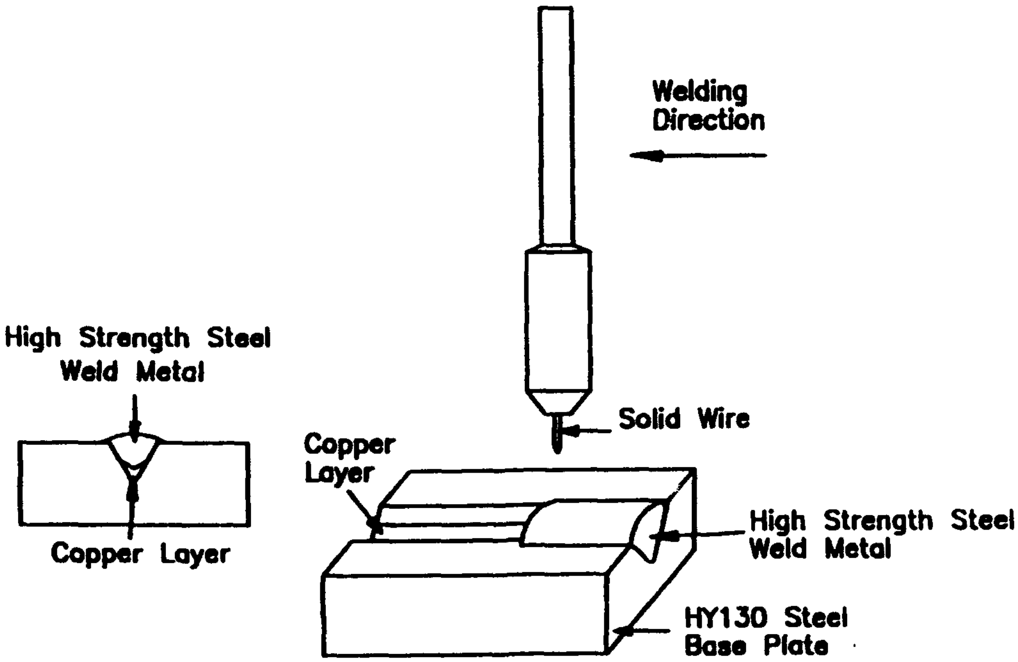
An Ar-CO_2 shielding gas and high purity niobium (99.8 wt. pct.) powder of particle size between one and five microns were used in these experiments. A suspension of niobium powder in acetone was prepared and deposited into the V-grooves. Depending on the desired niobium content in the weld metal, several coatings of niobium of different thicknesses were required. The low vaporization temperature of acetone, the small particle size of the powder, and the roughness of the as-machined V-grooved surfaces resulted in pure and well-adhered niobium layer. The melting and mixing of the niobium and the steel deposit occurred during welding. As in the other experiments, the HY-130 steel coupons were grit blasted to remove any paint or oxide scale and degreased prior to the application of the niobium "paint". The welding conditions were set to result in nominal heat inputs of 1.2, 2.4 and 3.6 kJ/mm (approximately 30, 60, and 90 kJ/in.), see Table III.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The findings of this research program will be summarized in five main sections. The first two will present a brief review of the results on oxygen and molybdenum additions. The following sections will discuss the influence of copper and/or niobium additions on HY-130 steel weld metals.



(a)



(b)

Figure 3. Schematic drawing of the experimental setup for copper additions.
(a) Deposition of copper layer of variable thickness;
(b) Deposition of HY-130 steel weld metal.

WELD METAL OXYGEN INVESTIGATION

The investigation into the influence of weld metal oxygen was performed to take advantage of the type, amount, and size distribution of non-metallic inclusions in achieving optimal weld metal microstructures and properties (22).

Inclusion size distribution is known to affect the prior austenite grain size and the formation of intragranular acicular ferrite. The presence of acicular ferrite in high stength steel weld metal also affects the final microstructure, as illustrated in Figure 4. Ramsay (15,22) indicated that a desirable inclusion size distribution generally consists of a bimodal size distribution, with significant number of inclusions smaller than the Zener diameter, d_{cr}. However, the population also exhibits a large number of inclusions of diameters larger than d_{cr}, as shown in Figure 5. It is expected that inclusions smaller than d_{cr} will limit austenite grain growth and inclusions larger than d_{cr} will promote the formation of ferrite laths within the austenite grains. These intragranular ferrite laths partition the prior austenite grains to originate smaller "effective" austenite grains which limit the size of the martensite laths. In addition, carbon rejection into the remaining austenite (as a result of ferrite formation) further refines the martensite laths.

Data shown in Figures 6 confirmed the mechanism proposed above. Both prior austenite grain size and martensite lath spacing decreased with increasing weld metal oxygen. This oxygen effect is real and reproducible, but requires excellent control of the oxygen potential of the weld system, which can be perturbed by variations in the welding consumables and insufficient weld pool protection from the atmosphere during welding. In fact, further analysis (22) showed that the effective use of inclusions in controlling the weld metal microstructure and enhancing the properties is limited to a narrow range of oxygen content, from 300 to 400 ppm. At oxygen levels lower than 300 ppm, insignificant amounts of acicular ferrite formed, insufficient to partition the prior austenite grains. At weld metal oxygen contents greater than 400 ppm, significant losses of essential alloying elements from the HY-130 steel weld metal occurred. With lower hardenability, the higher oxygen containing weld deposits failed to meet the minimum strength requirements. The decrease in strength of weld metals that contained higher amounts of oxygen as a function of heat input can be observed in Figure 7.

In the case of HY-130 steel weld metals, the minimum of 900 MPa in yield strength could only be achieved by a rigorous control of weld metal oxygen content and at lower welding heat inputs. It is apparent that an alternate strengthening mechanism must be identified to increase the strength even at higher heat inputs.

WELD METAL MOLYBDENUM INVESTIGATION

With the need of an alternate strengthening mechanism to further enhance the properties of the HY-130 steel weld metals, precipitation strengthening were evaluated.

Molybdenum additions from 0 to 3.5 wt. pct. were made to HY-130 steel weld deposits. An increase in weld metal hardness with increasing molybdenum content was observed (21). Furthermore, the weld metal hardness for each molybdenum content remained relatively constant with heat input, as shown in Figure 8. These results illustrate the effectiveness of molybdenum (in the form of molybdenum carbide precipitates) in broadening of the heat input range while maintaining weld metal strength. It was also observed that the highest strengthening effect of molybdenum in the 3.6 kJ/mm heat input welds took place between 0.5 to 0.9 wt. pct. molybdenum weld metal content, Figure 8. However, concerns about the effect of excessive molybdenum, above 0.5 wt. pct., which may reduce weld metal toughness, indicated the need of yet another precipitation strengthening agent.

Transformation Scheme

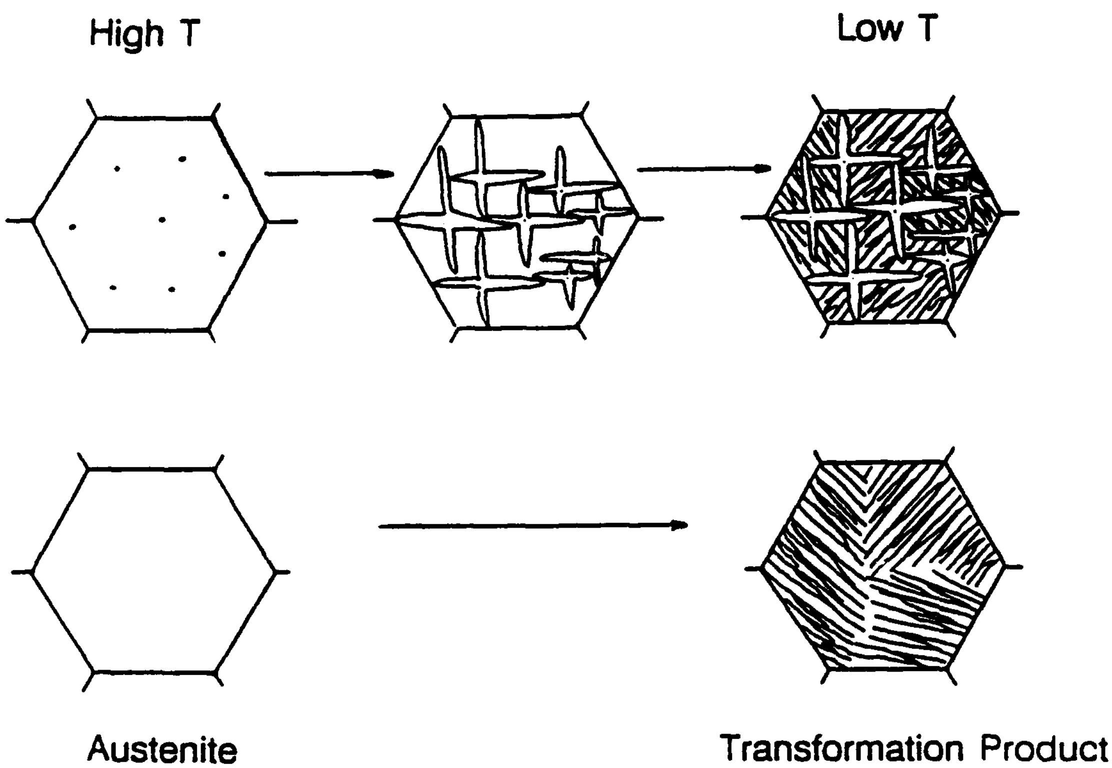


Figure 4. Proposed transformation model for high strength steel weld metal illustrating the effect of limited intragranular nucleation of acicular ferrite on the final microstructure (22).

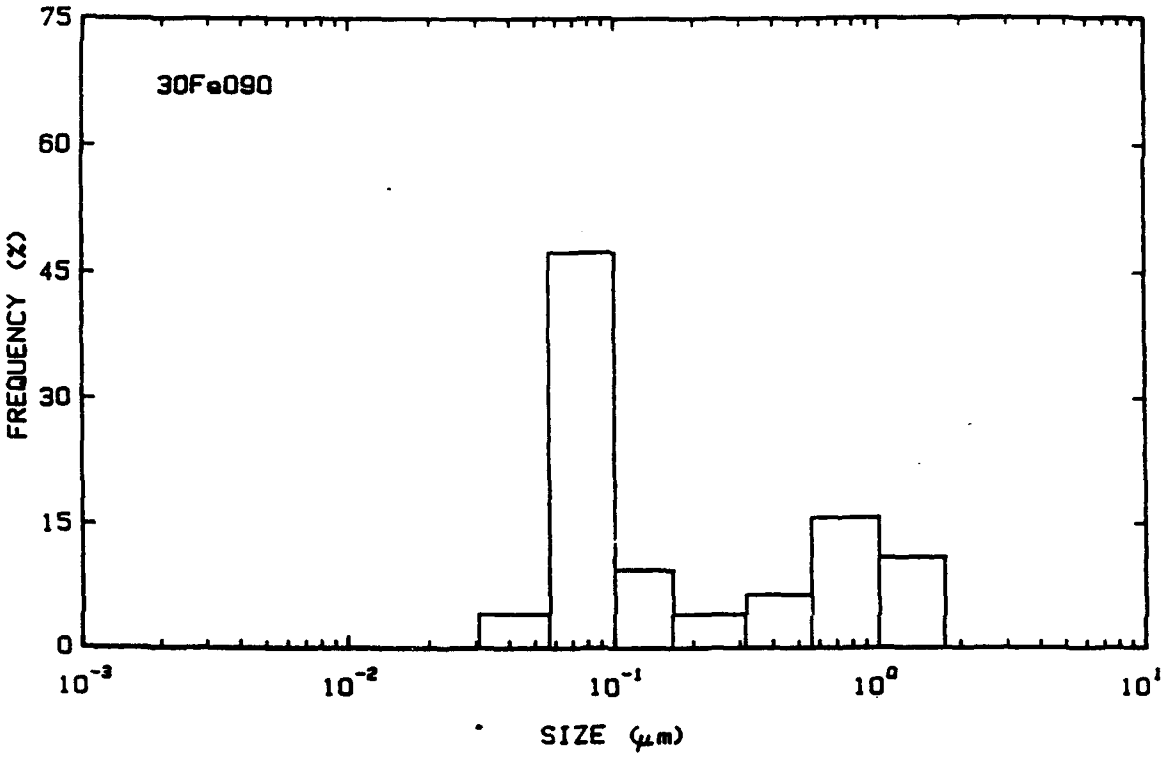


Figure 5. Size distribution of particles extracted from a HY-130 steel weld metal specimen with approximately 400 ppm of oxygen (22).

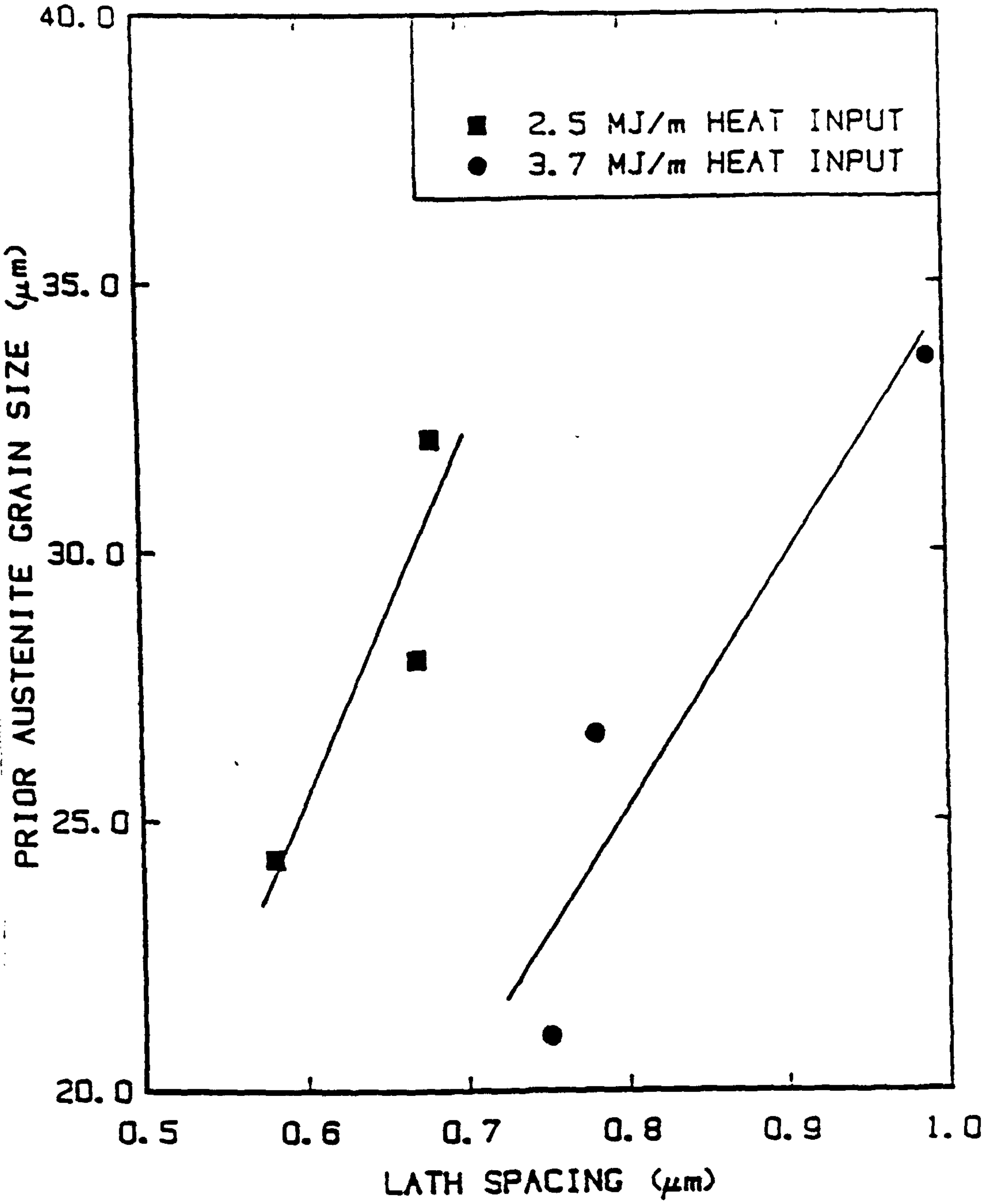


Figure 6. Correlation of lath spacing with prior austenite grain size for modified HY-130 steel weld metal specimens. The variation in prior austenite grain size and lath spacing are the result of variations in weld metal oxygen (22).

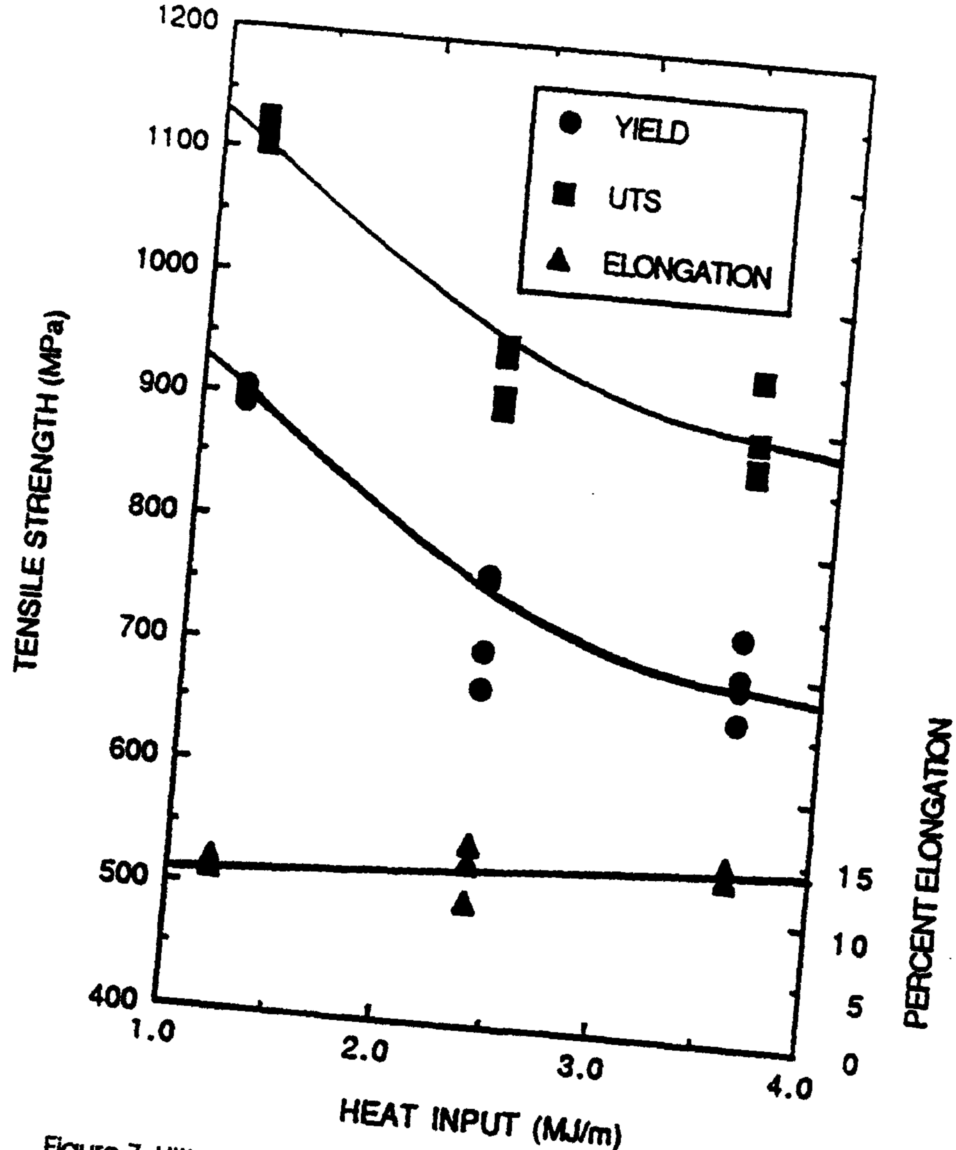


Figure 7. Ultimate tensile strength, 0.2% offset yield strength and total elongation to failure as a function of heat input for HY-130 steel weld metal with oxygen contents in the range of 450 to 650 ppm (22).

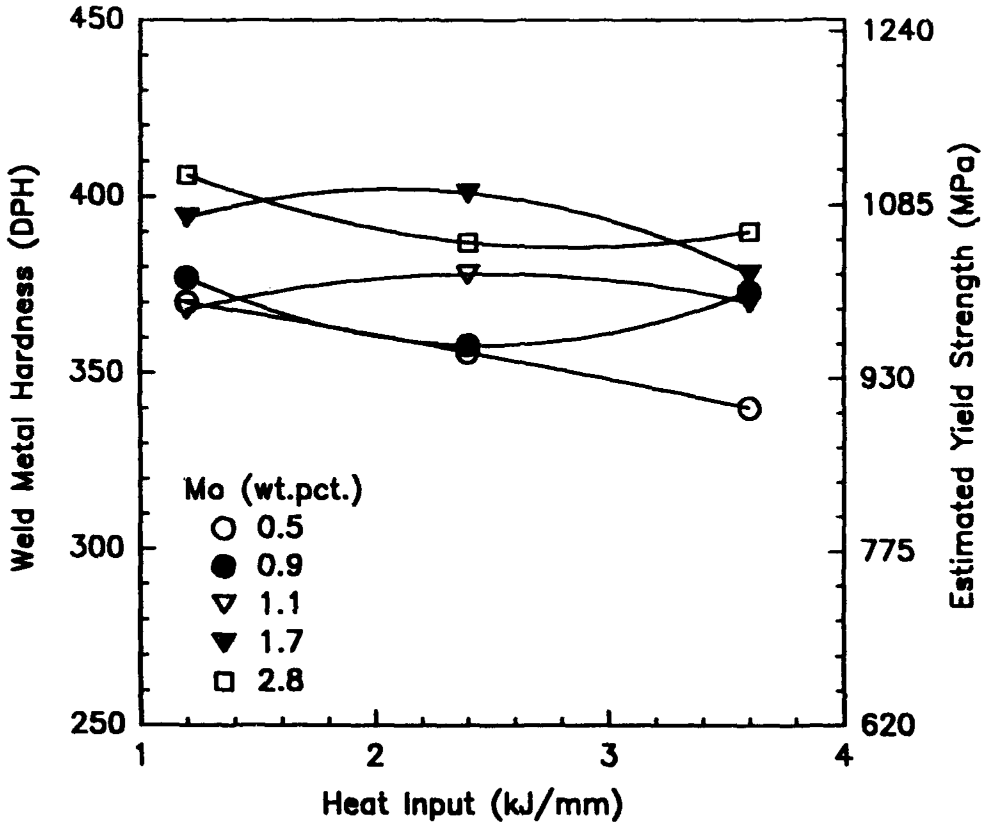


Figure 8. Diamond pyramid hardness (DPH) as a function of heat input and molybdenum content for modified HY-130 steel weld metal (21).

WELD METAL COPPER INVESTIGATION

With the need of another precipitation strengthening agent, systematic and controlled copper additions from 0 to 5.5 wt. pct. were made to the HY-130 steel weld deposits. Based on the reviewed literature (25-34), a model was proposed to explain the effect of copper precipitation on microstructure and properties of HY-130 steel weld metal at high heat input.

Mechanistic Interpretation of the Effect of Copper

Weld metal properties may be influenced by a number of different mechanisms, each of them dependent on the copper weld metal content. According to physical metallurgical principles, the overall effect of copper may be divided into the following main groups:

- Solid-Influence of copper in solid solution on the ferrite strength and toughness;
- Influence of copper on austenite/ferrite stability and on the refinement of the austenite decomposition products; and
- Influence of copper, in the form of precipitates on the ferrite strength.

The total yield strength of the weld metal, $_t$, can be expressed as:

$$\sigma_t = \sigma_i + \Delta\sigma_d + \Delta\sigma_{ss} + \Delta\sigma_{ppt}$$

Where σ_i is the strength component for the copper-free ferrite matrix. $\Delta\sigma_d$ is the strength increment due to grain refinement and best expressed as the Hall-Petch relationship. $\Delta\sigma_{ss}$ is the strength increment by solid solution of copper in iron. $\Delta\sigma_{ppt}$ is the strengthening effect of copper precipitation in the weld metal. Figure 9 shows schematically the strengthening effect of each of the mechanisms mentioned above.

Copper precipitation occurs when a critical amount of copper is added to the weld metal, that is, when the solubility limit of copper in iron is exceeded. Thus, strength enhancement due to copper precipitates, $\Delta\sigma_{ppt}$, will only manifest after the critical copper concentration has been reached. Obviously, this critical copper content is a function of the cooling rate; a faster cooled weld metal can retain a higher copper content in solution, as schematically illustrated in Figure 10. The curves labeled with copper concentrations are copper precipitation start curves. At 1.2 kJ/mm heat input, the weld metal can retain over 2.8 wt. pct. of copper without precipitation. At 3.6 kJ/mm, copper contents greater than 1.0 wt. pct. will precipitate. To fully utilize precipitation hardening during cooling, it is necessary to determine more precisely the critical copper content for a given cooling rate. With an adequately selected copper content for precipitation during cooling, a higher strength can be obtained in the HY-130 steel weld metals.

To test the mechanistic model described above, experiments to produce HY-130 steel welds with systematic additions of copper at different heat inputs, and thus different cooling rates, were carried out. The several copper contents obtained are reported in Table IV.

Table IV. Range of copper contents in the weld metal.

Weld (Wire) ID	Heat Input (kJ/mm)	Copper Content (wt. pct.)
A (1)	1.2	0.09 - 2.85
B (1)	2.4	0.08 - 5.50
C (1)	3.6	0.08 - 1.55
D (1)	3.6	0.30 - 3.72
E (2)	3.6	0.08 - 2.70

(D1) Lower cooling rate with bead morphology changes observed.

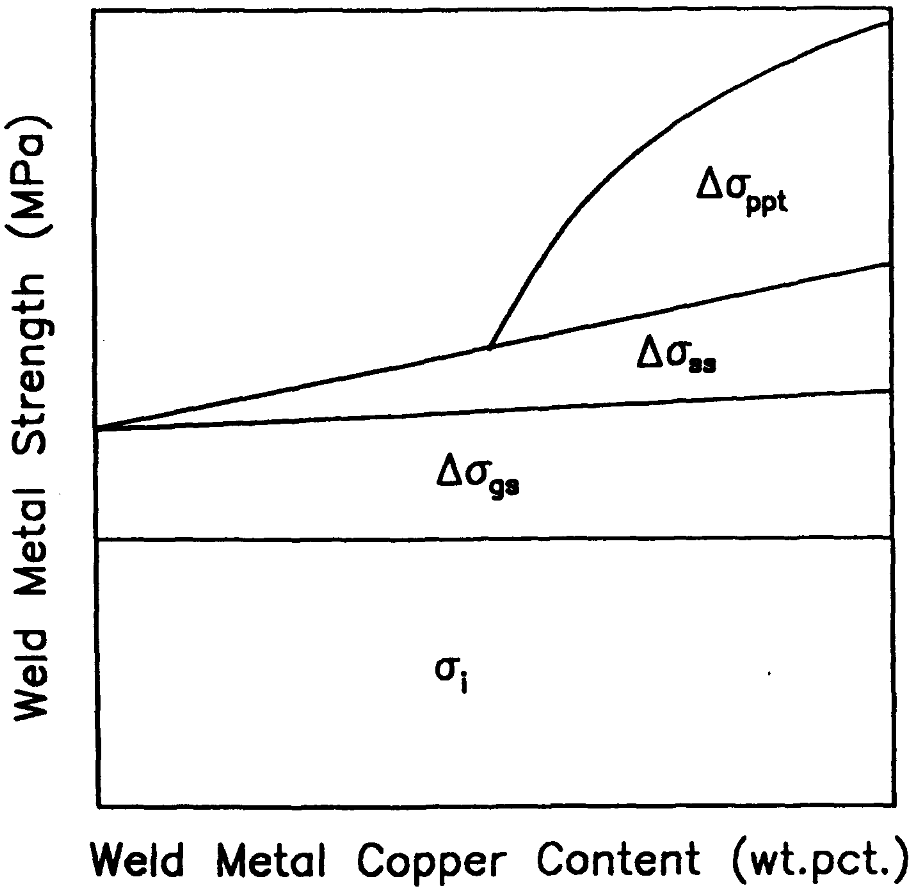


Figure 9. Schematic representation of weld metal strengthening by copper according to the different operating mechanisms.

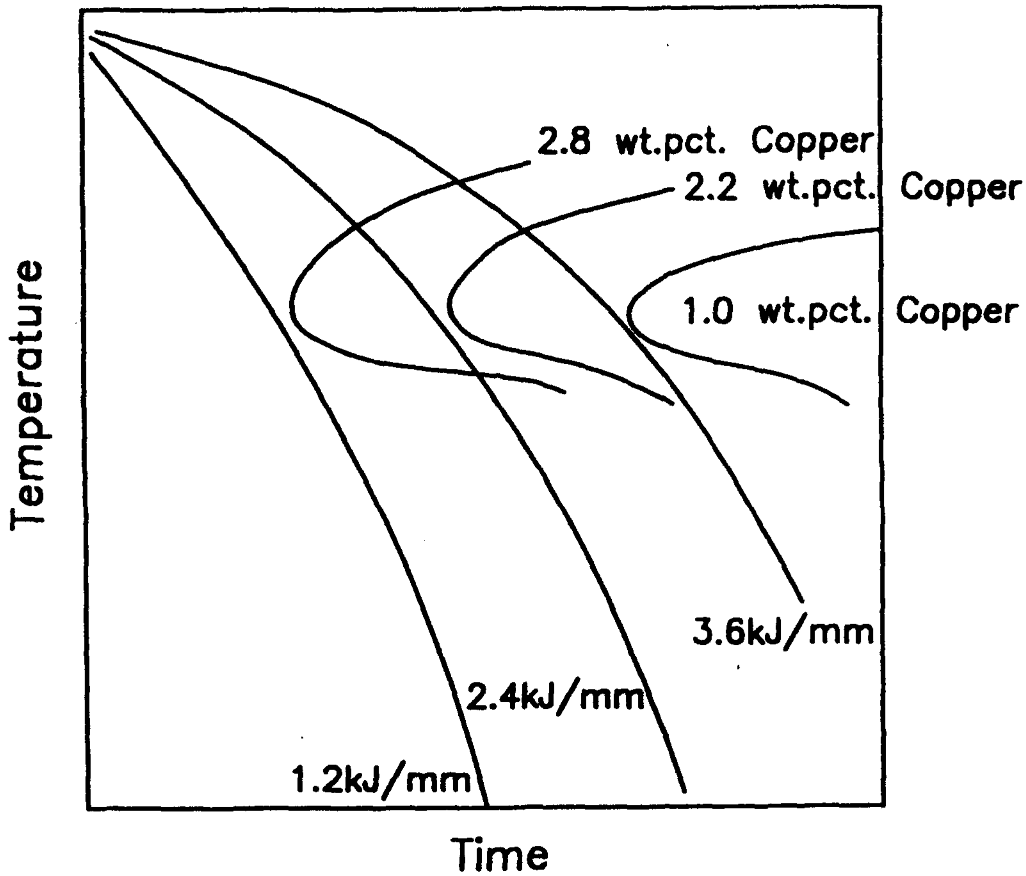


Figure 10. Schematic diagram illustrating the shift of copper precipitation curves with increasing copper addition.

Hardness and Microstructure of Reference Weld Metals

To characterize the effect of copper additions in HY-130 steel weld metal, some microstructural "baselines" were required. To establish a microstructural "baseline", reference weld metal deposits using available commercial welding wires (without any intentional alloying additions) were made at three heat input levels and evaluated for chemical composition, microstructure and hardness. To avoid the effects of welding fluxes and possible pickup of other elements, gas metal arc welding was used to generate these specimens.

An increase in heat input resulted in changes in both microstructure and mechanical properties of these reference weld metals. With increasing heat input, the weld metal microstructure changed from primarily martensitic to ferritic. In Figure 11, the hardness values of these reference weld metals are plotted as a function of weld metal cooling rate (inversely proportional to the heat inputs of 1.2, 2.4 and 3.6 kJ/mm, and plate thicknesses of 3/4, 1 and 2 in.). The hardness of the welds varied from approximately 400 to 290 HVN. Based on previous tensile and hardness data, a reference weld metal hardness of 360 HVN was determined to correspond to a yield strength of 900 MPa, minimum yield strength specified for the HY-130 high strength steel. Thus, the higher heat input welds (3.6 kJ/mm) with hardness below 360 HVN did not meet the strength requirement.

Weld Metal Hardness Change with Copper Additions

Figure 12 shows the weld metal hardness as a function of the weld metal copper content and welding heat input. In the case of low heat input welds, at 1.2 kJ/mm, copper concentration varied from 0 to 2.85 wt. pct. and the hardness was observed to decrease with copper additions. The softening of the weld metal with copper addition indicates that the critical content of copper for precipitation has not been reached. Therefore, strengthening due to copper precipitation in the low heat input welds is expected to take place at copper contents higher than 2.85 wt. pct. In the case of the medium heat input welds, at 2.4 kJ/mm, copper concentration varied from 0 to 5.5 wt. pct. and the hardness was observed to drop initially with copper content, followed by an increase. When copper content exceeded 2.2 wt. pct., the effect of copper precipitation strengthening was evident. Over four wt. pct., however, copper additions did not further increase the weld metal hardness; and significant variation in hardness was observed instead. For the high heat input welds, at 3.6 kJ/mm, the effect of strengthening can be interpreted as a result of two distinct mechanisms. Below 1.0 wt. pct. copper addition, only slight increase in hardness was observed. This increase is probably the result of copper solid solution strengthening the ferritic matrix. The increase in hardness became more noticeable when copper additions were higher than 1.0 wt. pct. and the more rapid strength increase can be attributed to copper precipitation in the weld metals. All these results support the proposed model that the copper content required for onset of precipitation strengthening increases with increasing weld cooling rate (decreasing heat input). Table V lists the critical copper contents and the weld heat inputs.

Table V. Critical copper content in HY-130 steel weld metals at different welding heat input.

Heat Input (kJ/mm)	Critical Copper Content (wt. pct.)
1.2	> 2.85
2.4	2.20
3.6	1.0

In the case of the 1.2 kJ/mm and 2.4 kJ/mm welds, the minimum estimated yield strength of the weld metal exceeded 900 MPa (130 ksi). This observation is not surprising because of the lower heat input and that martensitic/bainitic microstructure predominated in the weld metal. Without excep-

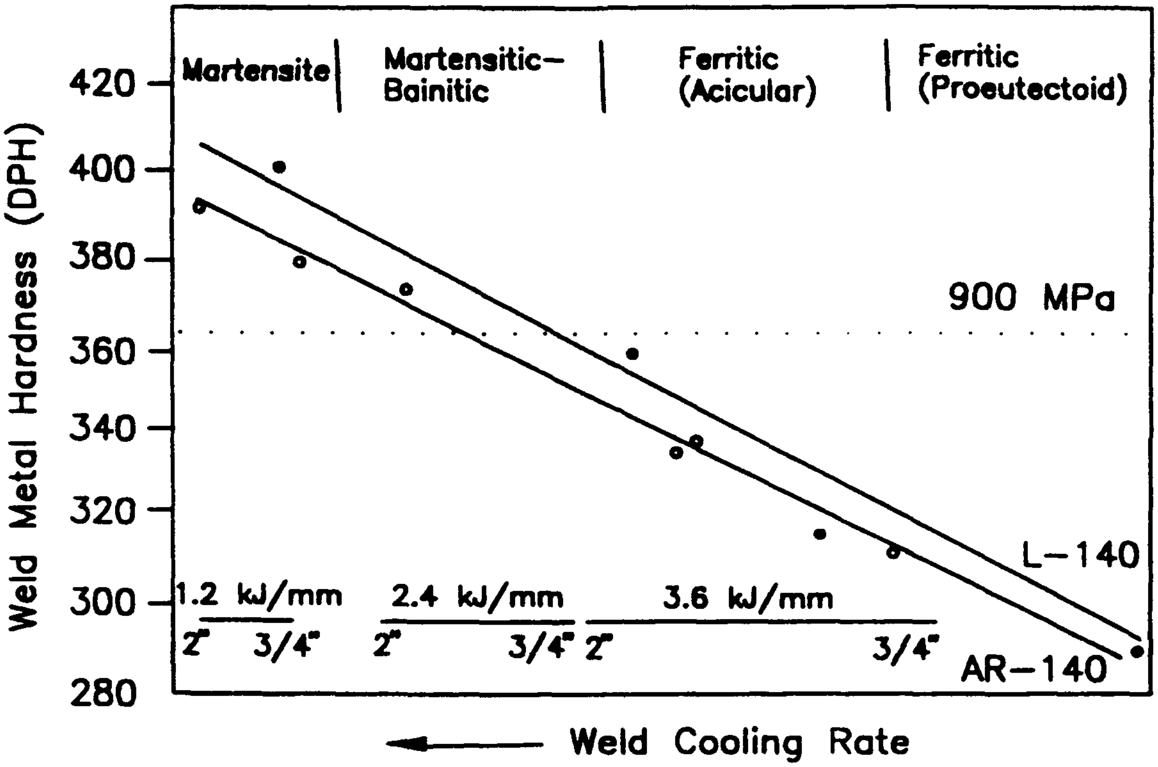


Figure 11. Hardness and microstructure of the reference weld metals, prepared using commercial welding wires without any intentional alloying additions, as a function of cooling rate.

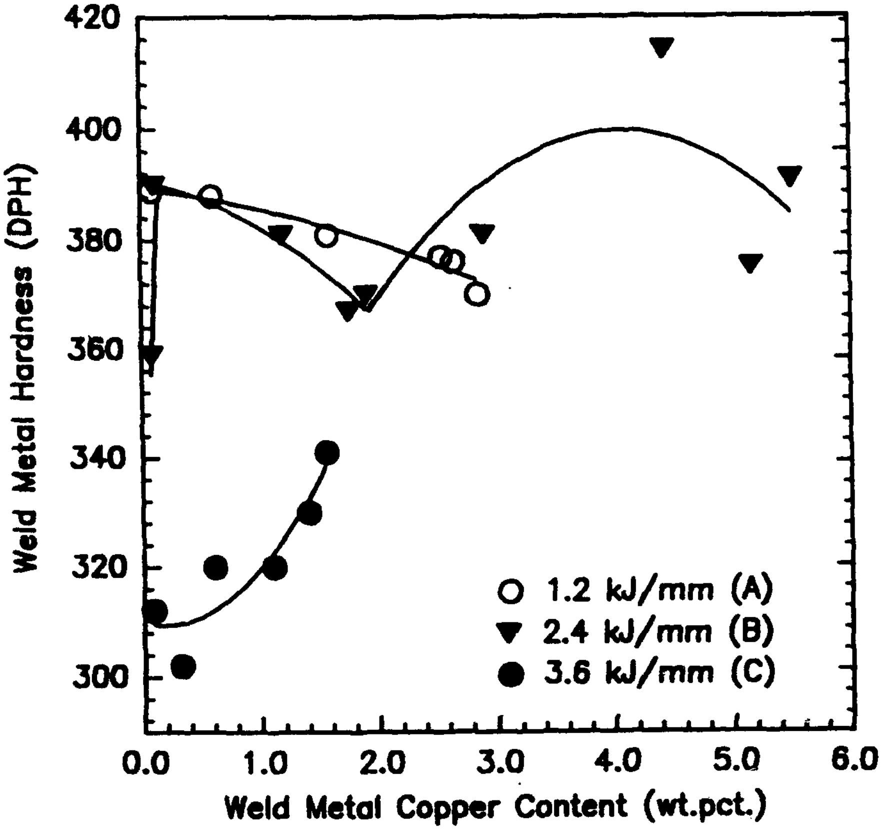


Figure 12. Hardness of the weld metal as a function of the weld metal copper content and welding heat input.

tion, the 3.6 kJ/mm welds exhibited much lower hardness and yield strength than the lower heat input welds. However, with 2.8 wt. pct. copper in the weld metal, the estimated yield strength of the high heat input weld metal was already equal to that of the base metal, approximately 900 MPa (130 ksi), as shown in Figure 13. This observation is significant because it shows the effectiveness of copper in strengthening high heat input welds, sufficient to satisfy the specified requirement for HY-130 steel welds. The effect of molybdenum can also be seen in Figure 13. For a constant level of copper addition, the weld metals with 0.63 wt. pct. of molybdenum exhibited higher hardness than the ones that contained 0.50 wt. pct. molybdenum. However, as discussed earlier, further addition of molybdenum is not recommended because of possible embrittlement (21).

Figure 14 summarizes the effect of copper additions in single pass welds. At fast weld cooling rates, that is, low heat input range, the weld metal hardness decreased with increasing weld metal copper content; but the estimated yield strength of the weld metal remained above the minimum required yield strength for the HY-130 steel. The decrease of weld metal hardness with copper additions may actually result in an improvement in the weld metal toughness, which is the main concern when using low heat input welding conditions. Being an austenite stabilizer, copper in solution tends to increase the amount of retained austenite in the alloy and decrease the hardness of the low and medium heat input weld metals. However, caution must be exercised because retained austenite in a martensitic/bainitic matrix has been related to stress corrosion cracking.

On the other hand, at lower weld cooling rates, that is, high heat input range, the weld metal hardness increased as the weld copper content was increased. This observation shows the effectiveness of copper precipitation to strengthen the high heat input weld metals. Combining the toughness of the ferritic matrix in the high heat input welds and the strengthening of the copper precipitation, it may be possible to obtain high strength and high toughness welds. In summary, copper additions to the weld metal seem to produce acceptable weld metal properties in a broad range of heat input. As an example, curve D in Figure 14 represents an HY-130 steel weld metal with 2.8 wt. pct. copper.

Multi-pass welding using copper strengthened weld deposits has shown a tendency to exhibit localized increases and drops in the weld metal hardness. These hardness fluctuations occurred at the reheated weld metals, as shown in Figure 15. The heating of a weld deposit by a later bead promotes the precipitation of ε-copper or aging of these precipitates that are already present, resulting in further hardening (385 HVN) or softening (280 HVN) of the reheated weld metal zone, as shown in Figure 15. This observation suggests that with copper additions alone as a precipitation strengthener, only the last bead deposited will have consistent through-bead hardness; but the prior reheated beads may experience significant hardness variations. To overcome the undesirable property variations, another precipitation agent in the weld metal is needed. The fundamental concept followed in this research was to introduce a second group of precipitates that would interact synergistically with the ε-copper precipitates to resist more effectively the multi-pass thermal cycles and minimize the hardness fluctuations observed throughout the weld beads.

WELD METAL NIOBIUM INVESTIGATION

With the need of a second precipitation strengthening agent, systematic niobium additions from 0 to 1.0 wt. pct. were made to HY-130 steel weld deposits. The selection of niobium was made after a careful evaluation of all alloying elements available and their potential effects on the properties of high strength steel weld metals (35-38).

The synergistic effect of copper and niobium in the weld metal is planned to be two fold. First, the formation of niobium carbide precipitates is expected to reduce the amount of free carbon in the matrix

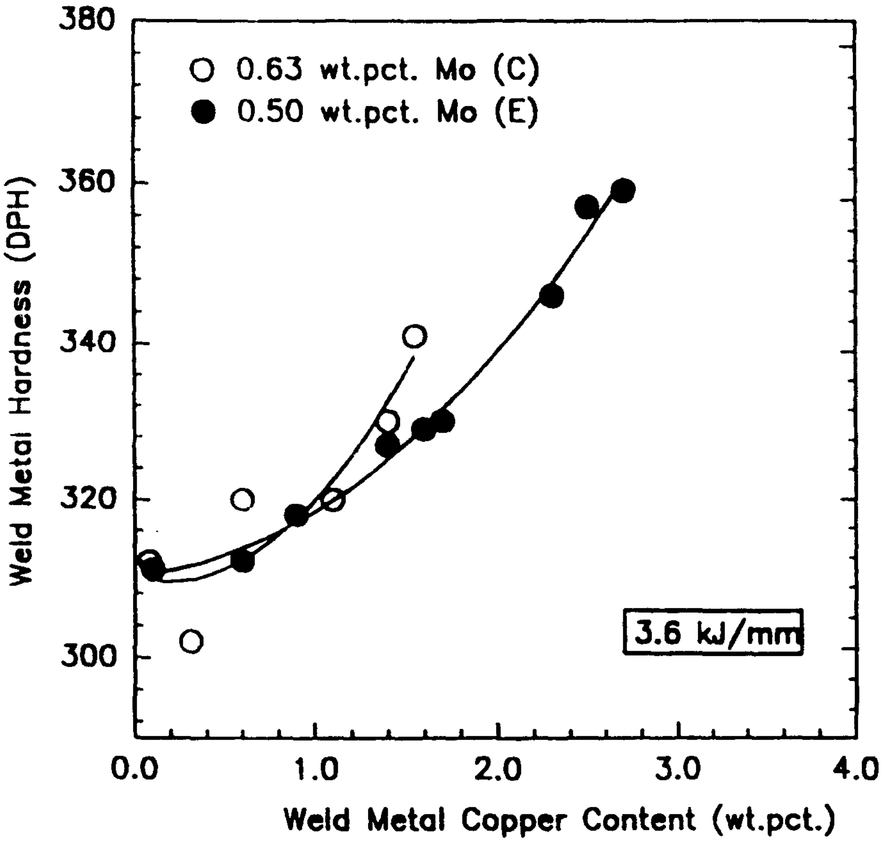


Figure 13. High heat input weld metal hardness as a function of weld metal copper content.

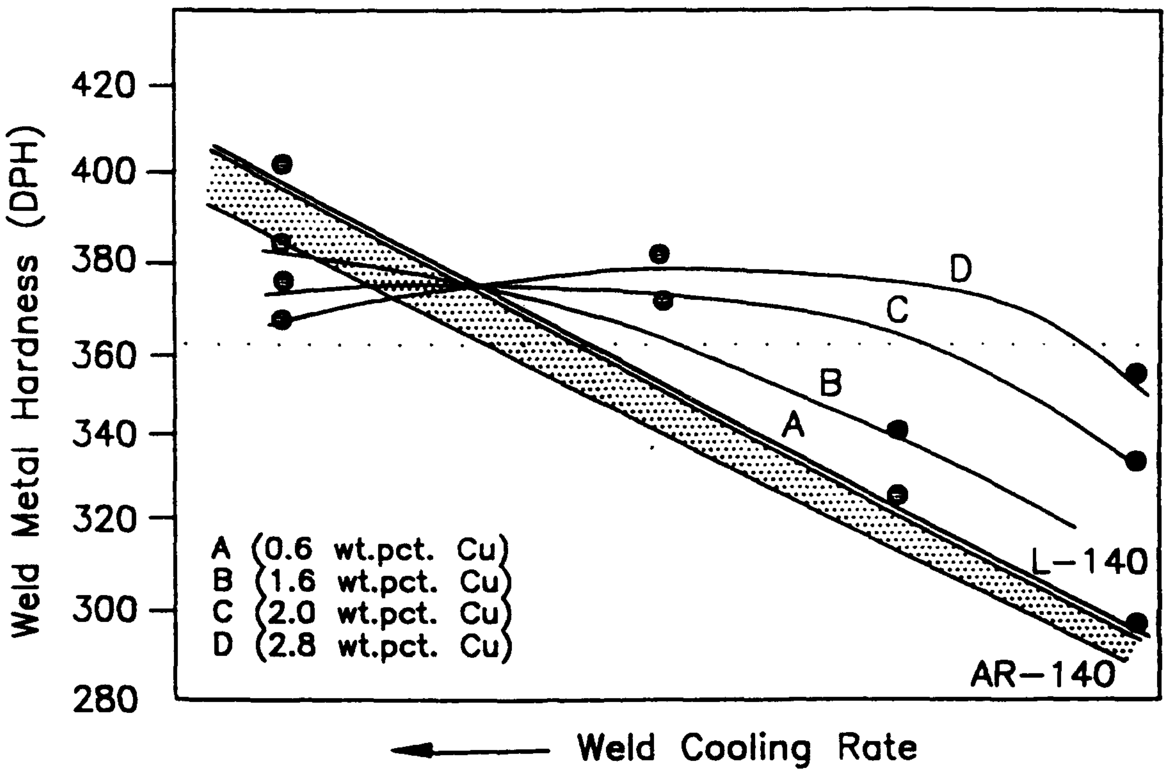


Figure 14. HY-130 steel weld metal hardness as a function of weld metal copper content and cooling rate.

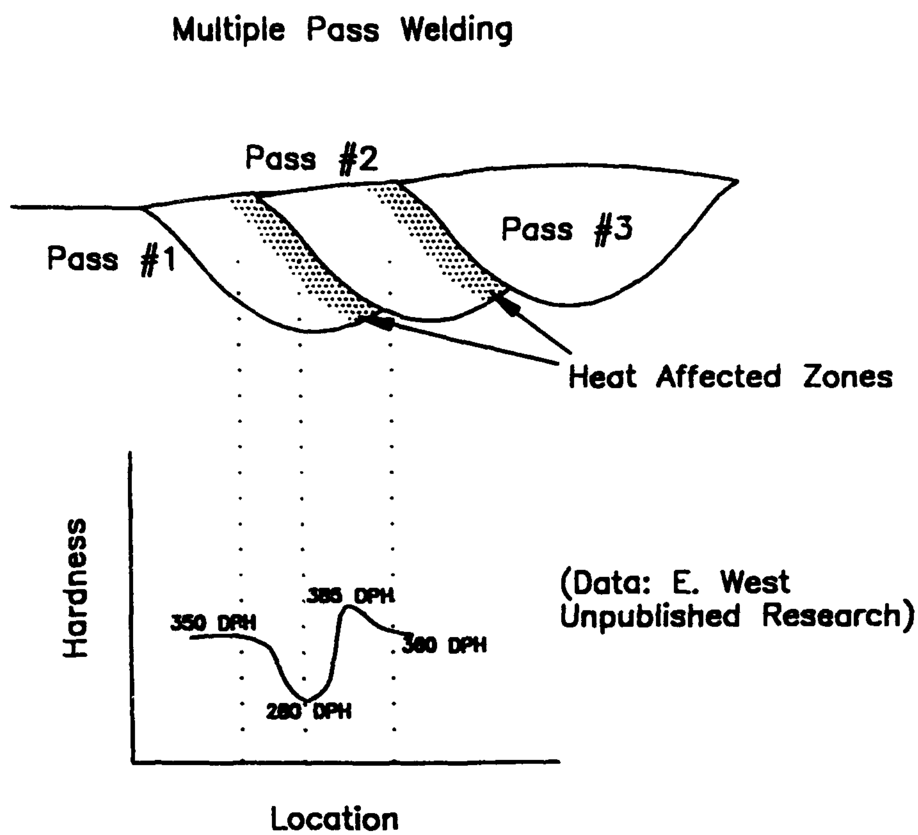


Figure 15. Localized drops in weld metal hardness in the reheated weld metal of an earlier deposited copper strengthened weld bead during multi-pass welding.

and affect the segregation pattern of copper and niobium in the weld metal. Therefore, the normal pattern of high carbon regions alternating with high copper regions, due to the poor chemical affinity between copper and carbon (35), is expected to decrease. As a result, better spatial distribution of the precipitates (both ε-copper and niobium carbide) in the matrix and more uniform mechanical properties are anticipated. Second, The combination of two kinds of precipitates with different thermal stability and distinct precipitation reaction kinetics is expected to provide a better overall strengthening effect to the weld metal. Niobium carbides are more stable at high temperature than the ε-copper precipitates and yet they precipitate slowly in iron alloys (36-38), as illustrated schematically in Figure 16. While the ε-copper precipitates coarsen and lose their hardening effect as a result of the thermal cycle, the niobium precipitates nucleate and age to provide a hardening effect. Therefore, the dual precipitation scheme is expected to reduce the hardness fluctuation and produce high strength steel weld metals with acceptable properties in a wide range of heat input welding condition during single and multipass welding.

Weld Metal Hardness Change with Niobium Additions

Figure 17 shows the weld metal hardness as a function of the weld metal niobium content and welding heat input in single pass welding. In the case of low and medium heat input welds, at 1.2 kJ/mm and 2.4 kJ/mm, the hardness was observed to increase with niobium additions and reached 420 and 380 HVN at approximately 0.15 wt. pct. and 0.10 wt. pct. niobium content, respectively. This hardening behavior with low niobium additions may be the result of the solid solution strengthening of the martensitic-bainitic matrix by niobium. Even though the hardness decreased with higher levels of niobium additions, the decrease is of minor concern since niobium addition up to 0.1 wt. pct. in the weld metal is considered to be the recommended range. For the high heat input welds, at 3.6 kJ/mm, the hardness was observed to increase only slightly with niobium additions. This slight hardening effect can be interpreted as strengthening of the ferritic matrix by niobium in solid solution. Therefore, niobium provides only a small strengthening effect on high heat input single pass weld metals. In general, this observation indicates that a level of niobium additions higher than 0.35 wt. pct. is required to produce a reasonable strengthening effect during the thermal cycle of a high heat input single pass welding process. However, higher levels of niobium additions have not been considered due to the possible embrittling effect of niobium.

WELD METAL COPPER-NIOBIUM INVESTIGATION

The observed effect of copper and niobium, when added individually, on the weld metal hardness can be summarized as follows: at low and medium heat input, 1.2 kJ/mm and 2.4 kJ/mm, acceptable weld metal hardness, that is, above 360 HVN, can be obtained with either 0.11 wt. pct. copper or 0.15 wt. pct. niobium. At high heat input, 3.6 kJ/mm, a copper addition of 2.8 wt. pct. is required to obtain 360 HVN in the weld metal, which corresponds to an estimated yield strength of 900 MPa. Niobium provided inadequate strengthening in high heat input weld metals.

Therefore, controlled additions of up to 3.5 wt. pct. copper and up to 0.45 wt. pct. niobium were made to the weld metals to evaluate the synergistic effect of copper and niobium in high heat input weld metals. The copper and niobium additions were made using the experimental procedures explained previously, buttered layers of copper using gas tungsten arc welding, and brushed layers of the niobium "paint".

Weld Metal Hardness Change with Copper-niobium Additions

Figure 18 shows the high heat input weld metal hardness as a function of copper and niobium content in the weld metal. The hardness data with copper as a single alloying addition have been included (solid curve in Figure 18) for comparison and evaluation of the synergistic strengthening effect of copper and niobium in the weld metal.

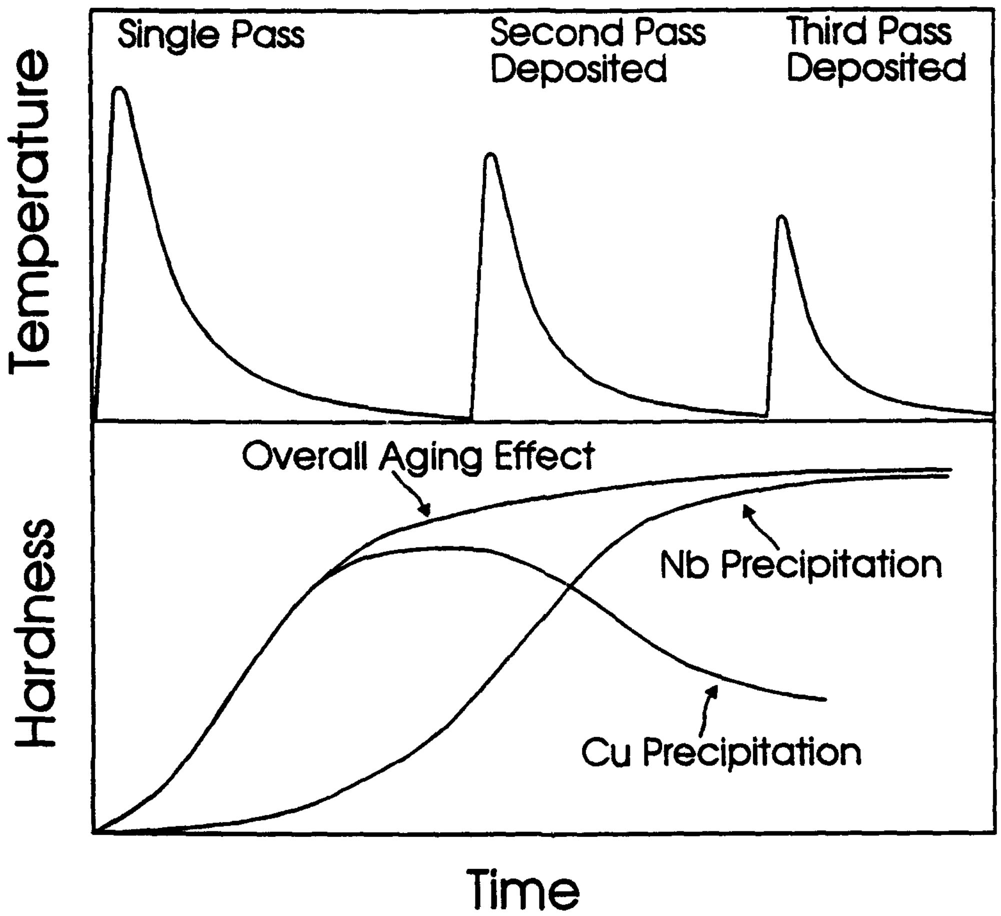


Figure 16. Schematic diagram illustrating the dual precipitation scheme during single and multi-pass welding.

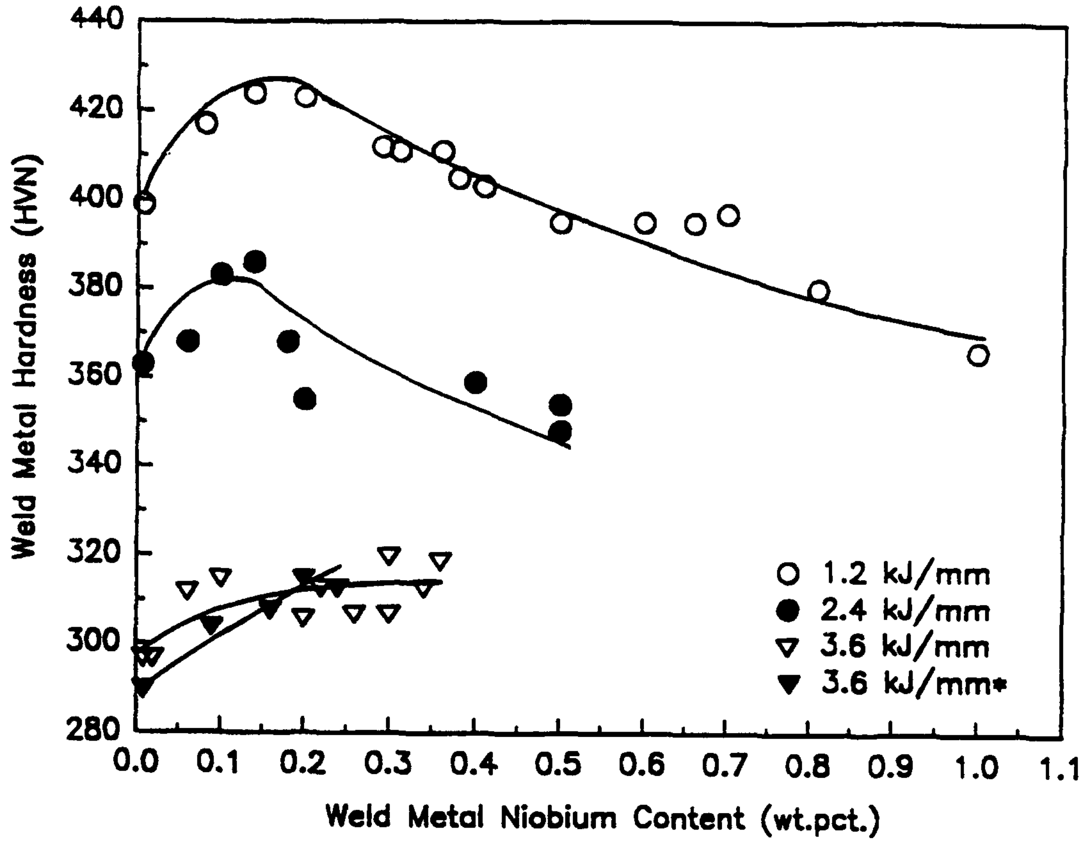


Figure 17. Weld metal hardness as a function of heat input and niobium content for modified HY-130 steel weld metal.

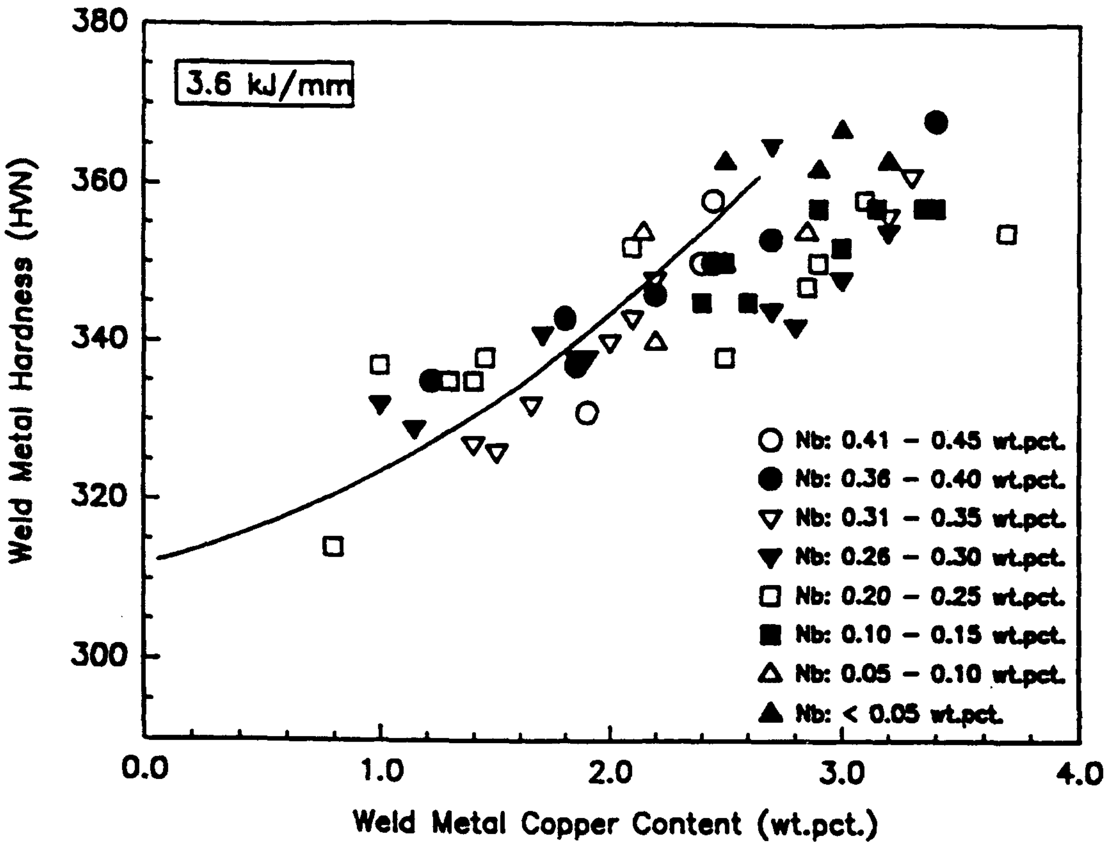


Figure 18. High heat input (3.6 kJ/mm) weld metal hardness as a function of copper and niobium content in the weld metal.

In general, the observed trend of the weld metal hardness with copper-niobium additions follows the same trend of the weld metal hardness with copper additions. This observation implies that copper precipitation is the main strengthening mechanism while niobium exerts only secondary influence in a high heat input single pass weld metal.

On the other hand, when the weld metal copper content exceeded 2.5 wt. pct., an interesting behavior of the weld metal hardness as a function of copper and niobium additions was observed and shown in Figure 19. Only three ranges of niobium content in the weld metal have been included in this figure for the sake of clarity of illustration. At higher levels of niobium content (0.2-0.35 wt. pct.), the hardnesses of the copper-niobium enhanced weld metals were lower and more irregular as compared to those of the copper-enhanced weld metal; but at lower levels of weld metal niobium content (approximately 0.05 wt. pct.), the weld metal hardness readings were uniform and reflected acceptable strength. This observed behavior of the weld metal hardness clearly manifests the result of the synergistic effect of copper and niobium on the segregation pattern of these two elements in the weld metal as discussed previously. Therefore, niobium addition levels lower than 0.1 wt. pct. are considered as appropriate to avoid the irregular hardness of the copper-niobium enhanced weld metal observed.

Multi-pass Welding of Copper-niobium Enhanced Weld Metals

To evaluate the synergistic effect of copper and niobium in the weld metal during multi-pass welding, systematic additions of copper from 3.2 to 3.7 wt. pct. and addition of niobium from 0 to 0.44 wt. pct. were made to HY-130 steel weld deposits.

The welding conditions were set to the three heat input levels, as reported in Table III. The reheated weld metal in the first bead, starting from the fusion line of the second pass as illustrated schematically in Figure 20, was evaluated for chemical analysis and microhardness. The chemical analysis were carried out using a scanning electron microscope with electron microprobe analysis capability to determine the composition profile of copper and niobium along the reheated weld metal zone. A microhardness profile along the reheated weld metal zone was determined as well.

Figures 21a to 21g show the microhardness and composition profiles of copper and niobium along the reheated zones of the weld metal deposits made at the three different heat inputs. In the broad range of welding conditions used, the weld metal hardness of the reheated zone is generally higher or equal to the reference weld metal hardness of 360 HVN (estimated yield strength of 900 MPa) and the reheated zones of the copper-niobium enhanced weld metals did not experience the drastic changes in weld metal hardness as was observed in the copper enhanced multi-pass weld metals, Figure 15. These results are a manifestation of the synergistic effect of copper and niobium in the high strength steel weld metals during multi-pass welding. Therefore, the copper-niobium additions have proven to be adequate to produce acceptable weld metal hardness in the broad range of heat input welding conditions.

On the other hand, the same behavior (changes of weld metal hardness with the amount of niobium content) that was observed in single pass deposits is also experienced in multi-pass welding. A niobium content higher than 0.2 wt. pct. produced a more erratic (compare Figure 21c and Figure 21d) and lower weld metal hardness (Figures 21e to 21g) profile.

In summary, the concept of dual precipitation strengthening with copper and niobium showed great promise in providing the required hardness/strength and in reducing the hardness fluctuations observed in the single precipitation welds. Additions of approximately 3.3 wt. pct. copper and up to 0.1 wt. pct. niobium in the weld metal exhibited the strengthening effect to obtain high strength steel weld

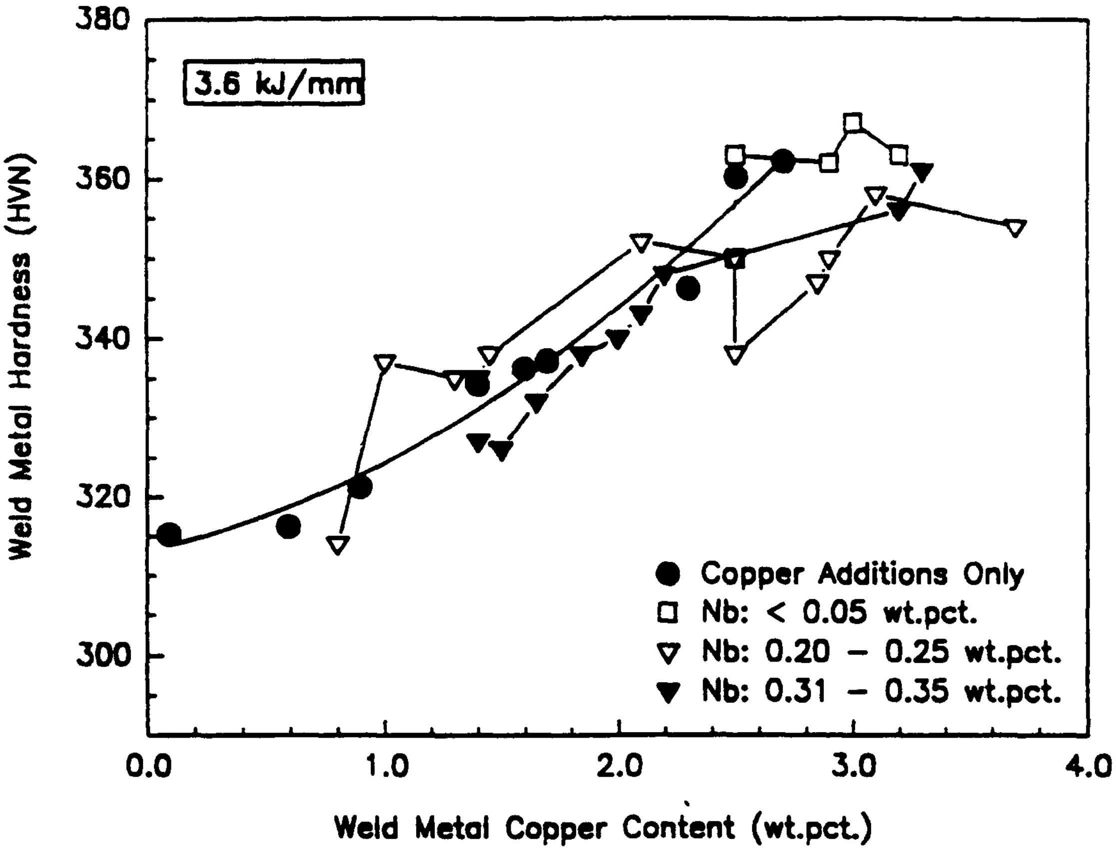


Figure 19. High heat input (3.6 kJ/mm) weld metal hardness as a function of copper and niobium content in the weld metal.

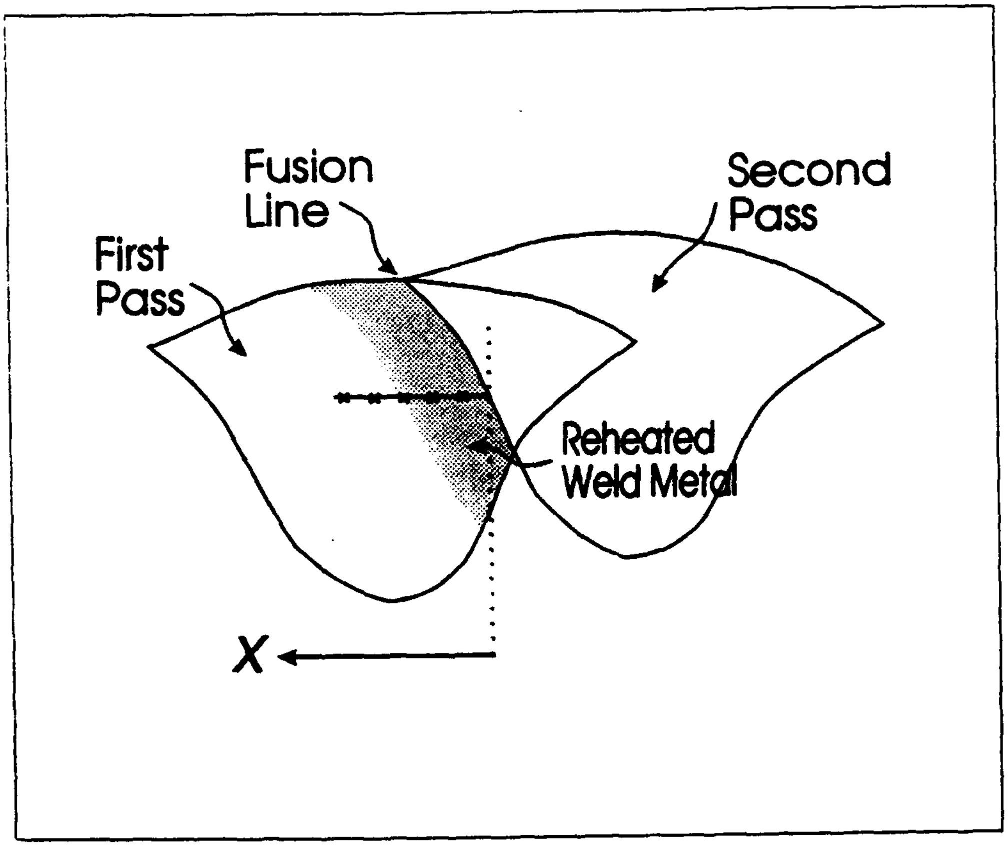


Figure 20. Schematic drawing illustrating the reheated zone in a weld bead during multi-pass welding. The points indicate the locations where chemical composition and hardness measurements were taken.

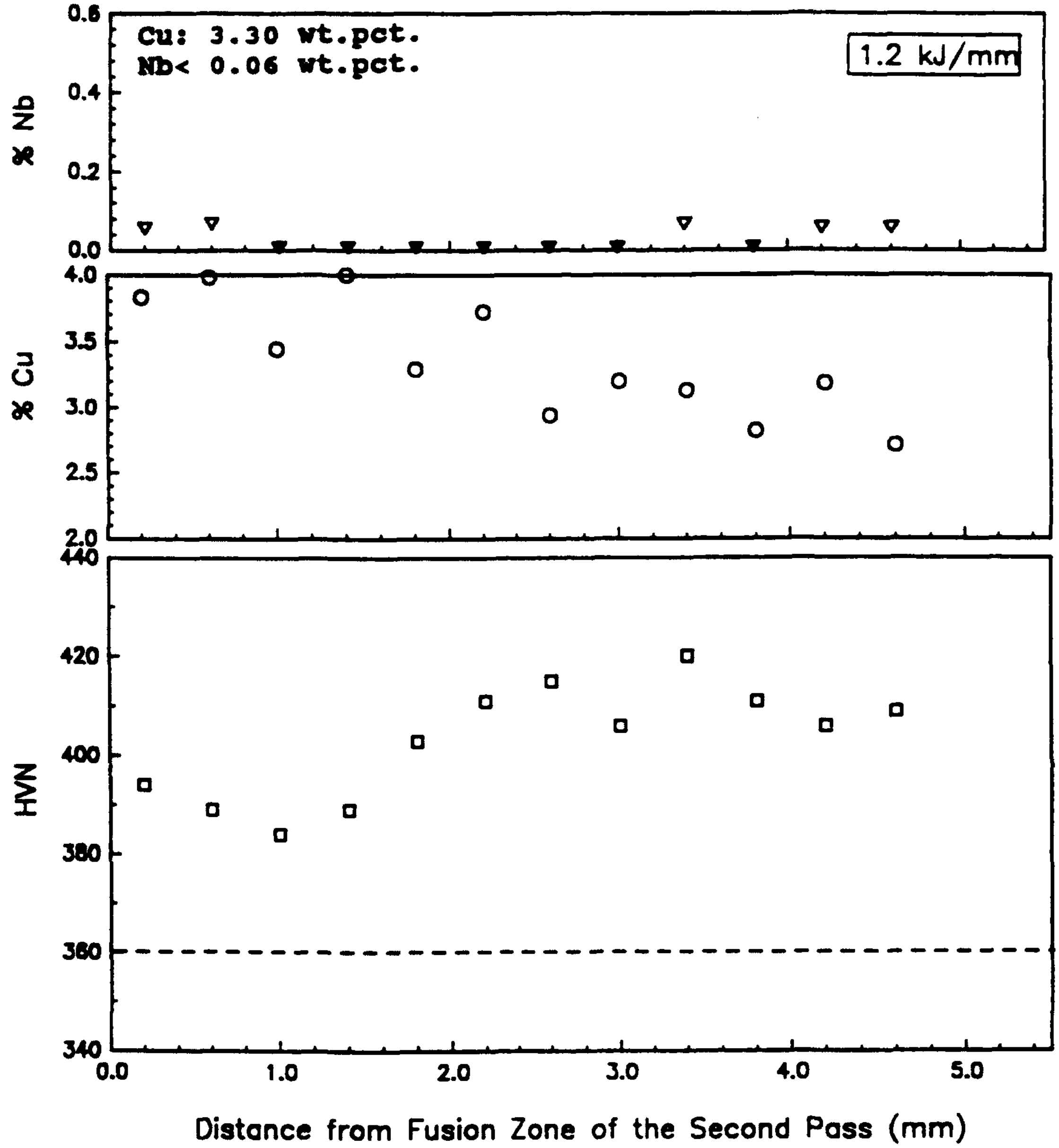


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (a) 1.2 kJ/mm - 3.30 wt. pct. Cu and 0.06 wt. pct. Nb.

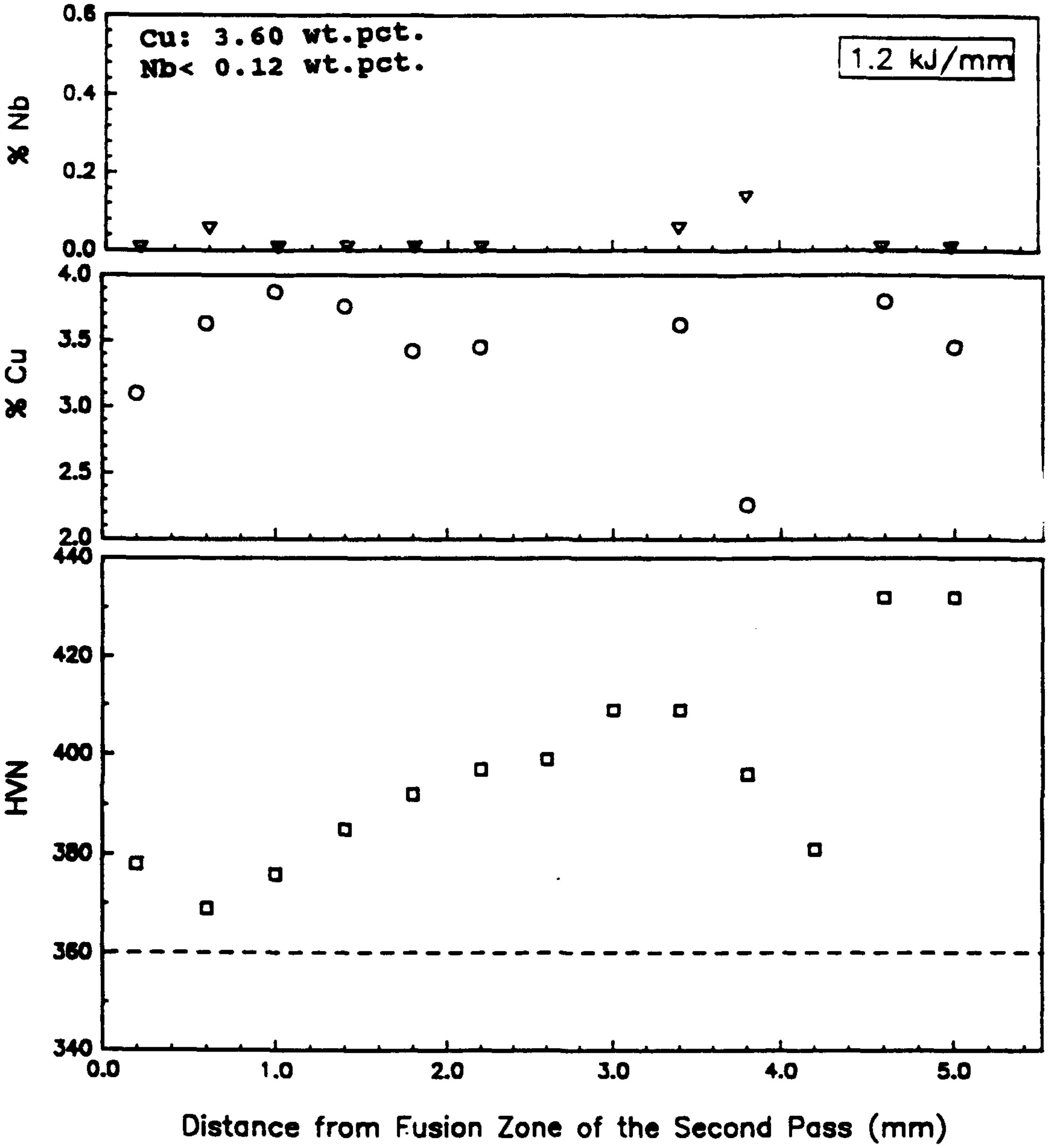


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (b) 1.2 kJ/mm - 3.60 wt. pct. Cu and 0.12 wt. pct. Nb.

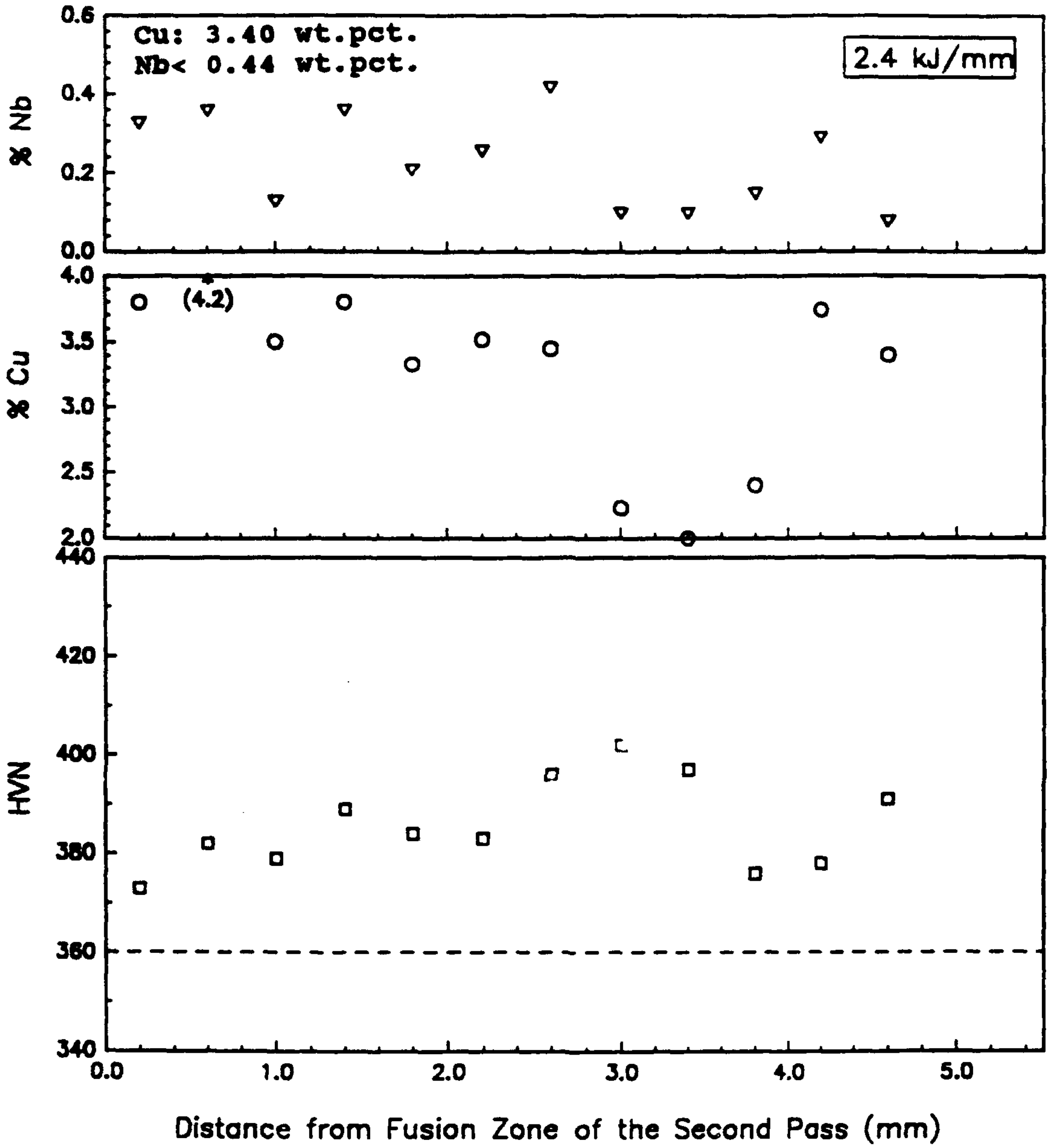


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (c) 2.4 kJ/mm - 3.40 wt. pct. Cu and 0.44 wt. pct. Nb.

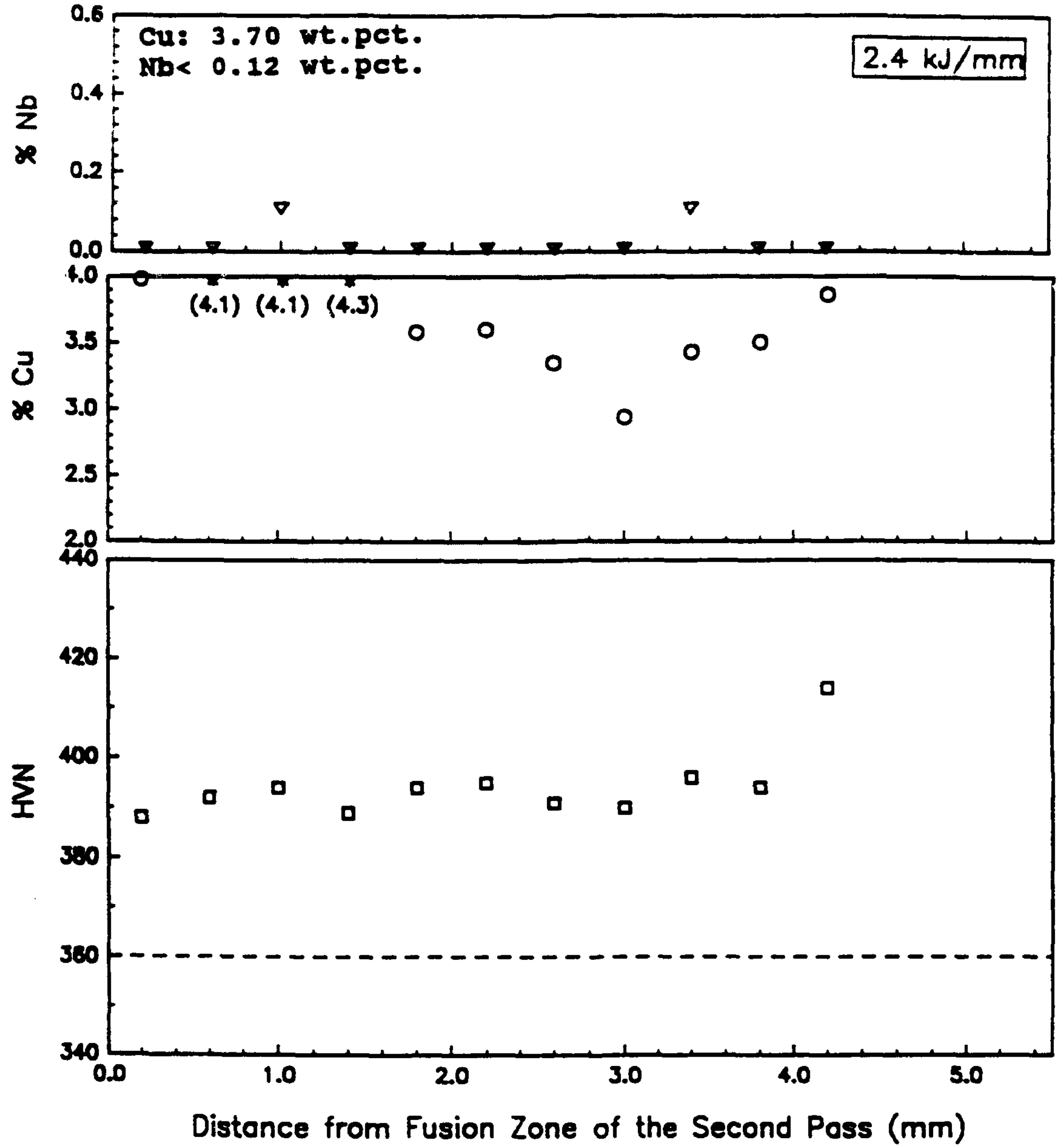


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (d) 2.4 kJ/mm - 3.70 wt. pct. Cu and 0.12 wt. pct. Nb.

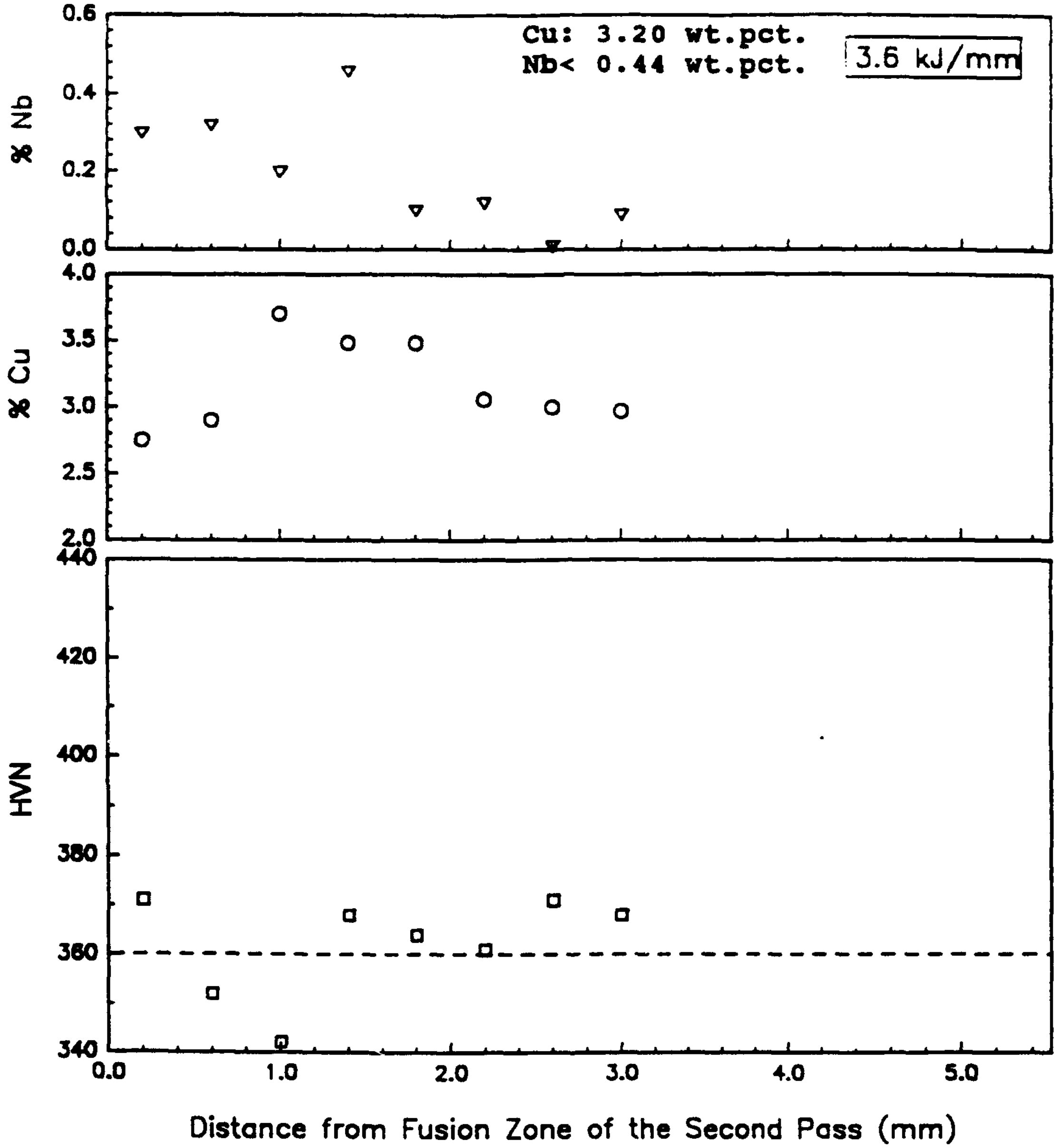


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (e) 3.6 kJ/mm - 3.20 wt. pct. Cu and 0.44 wt. pct. Nb.

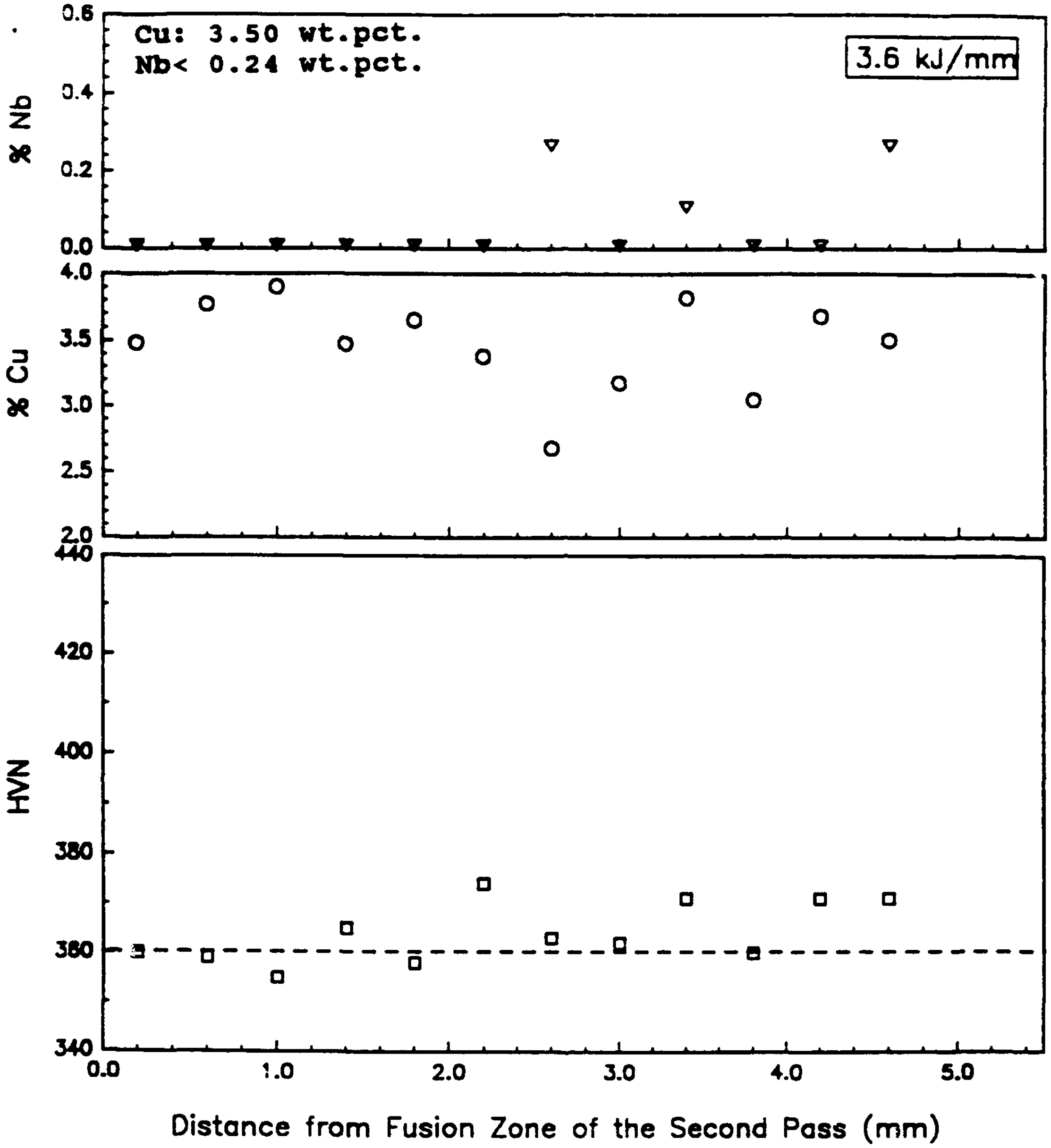


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (f) 3.6 kJ/mm - 3.50 wt. pct. Cu and 0.24 wt. pct. Nb.

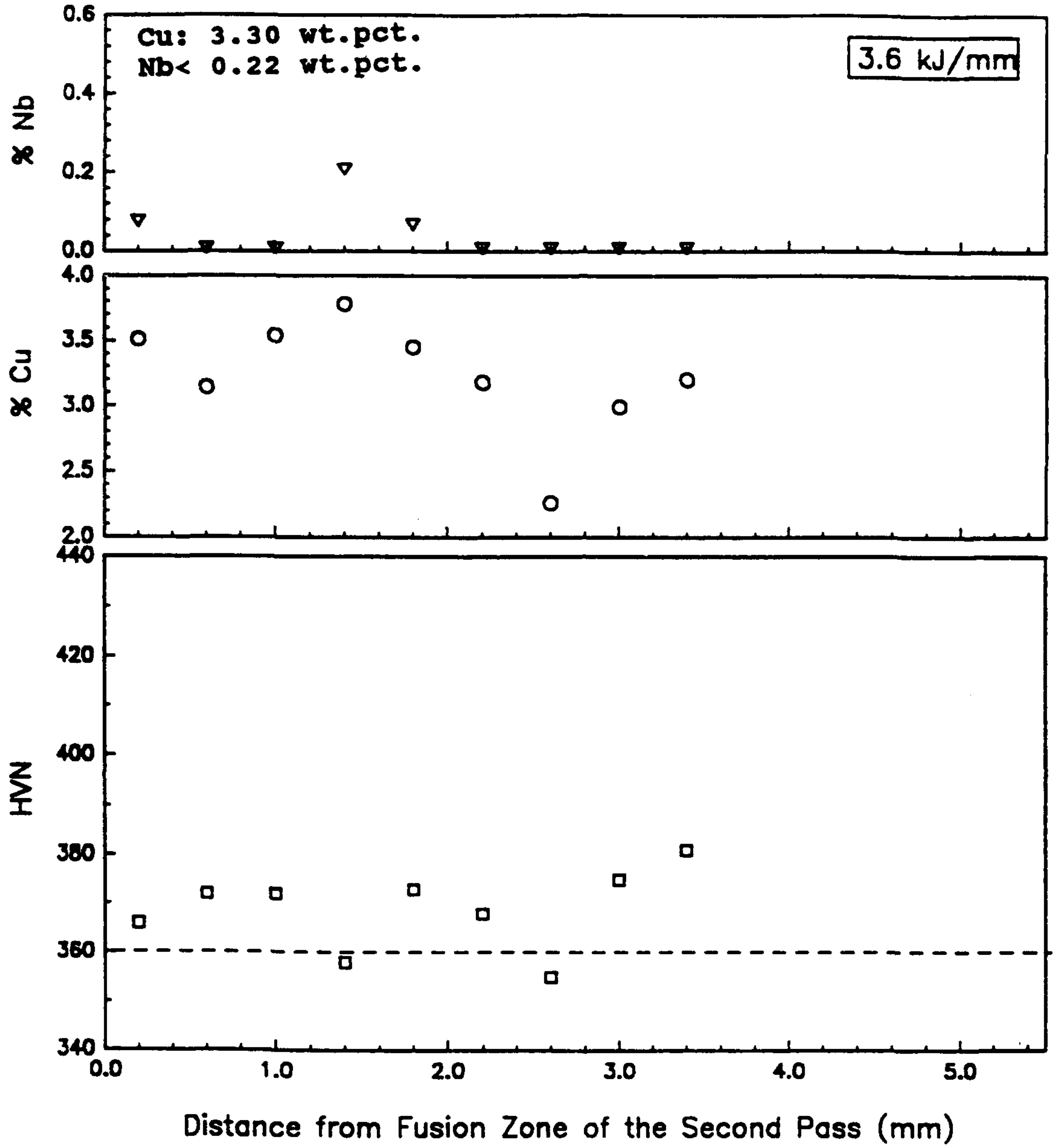


Figure 21 a to g. Weld metal microhardness profiles, and copper and niobium omposition profiles across the reheated weld metal during multi-pass welding. (g) 3.6 kJ/mm - 3.30 wt. pct. Cu and 0.22 wt. pct. Nb.

metals with acceptable properties in an extended range of heat input welding condition during single and multi-pass welding. See schematic representation in Figure 22.

ACCOMPLISHMENTS TO DATE

The major accomplishments of this research program are listed in the following:

1. Even though weld metal oxygen is a method to achieve a broader heat input range and still obtain adequate properties, its application is limited due to the precise control required and the susceptibility of oxygen pickup from the welding environment.

2. Weld metal molybdenum additions increase the HY-130 steel weld metal yield strength to nearly the required strength level over the extended heat input range (1.2 to 3.6 kJ/mm). However, excessive use of molybdenum, above 0.5 Wt. pct., may degrade weld metal toughness.

3. Copper additions in the weld metal can increase the hardness and yield strength. This strengthening can be correlated to ε-copper precipitation. A mechanistic model has been proposed to explain the observed results.

4. Strengthening of HY-130 steel weld metals due to copper precipitation (one inch thick base plate) required a minimum of 1.0, 2.2, and above 2.85 wt. pct. of copper for 3.6, 2.4, and 1.2 kJ/mm welding heat input, respectively.

5. Copper precipitation is very effective in strengthening HY-130 steel weld metal at high heat input (3.6 kJ/mm). An increment of approximately 35 HVN (110 MPa) per wt. pct. of copper was observed in the range of 1.0 to 2.8 wt. pct. weld metal copper content.

6. Copper precipitation is less effective in strengthening martensitic-bainitic weld metals (at medium heat input). An increment of approximately 13 HVN (40 MPa) per wt. pct. of copper was observed in the range of 2.2 to 4.5 wt. pct. weld metal copper content.

7. Copper-modified welding wires that will result in 2.8 wt. pct. weld metal copper content will produce acceptable weld metal properties (hardness and yield strength) in HY-130 steel welding, in a broad range of weld cooling rates (heat input and plate thickness combinations).

8. Reheated weld deposits that contained copper are subjected to hardness variations across multipass welds due to overaging. Precipitation agents other than copper, such as niobium, are needed to synergistically interact with copper to minimize such non-uniform weld properties.

9. Weld metal niobium contents lower than 0.15 wt. pct. were found to be effective in strengthening the low and medium heat input steel weld metal. However, niobium was less effective in strengthening the high heat input weld metals.

10. Copper addition of 3.0 wt. pct. with niobium additions up to 0.05 wt. pct. produced weld metals with 360 HVN. High level of niobium, up to 0.45 wt. pct. was observed to decrease the weld metal hardness and to increase the copper content fluctuations in the weld metal.

11. Reheated weld deposits that contain approximately 3.3 wt. pct. of copper and up to 0.1 wt. pct. niobium exhibited adequate weld metal hardness, equal to or higher than 360 HVN which corresponds

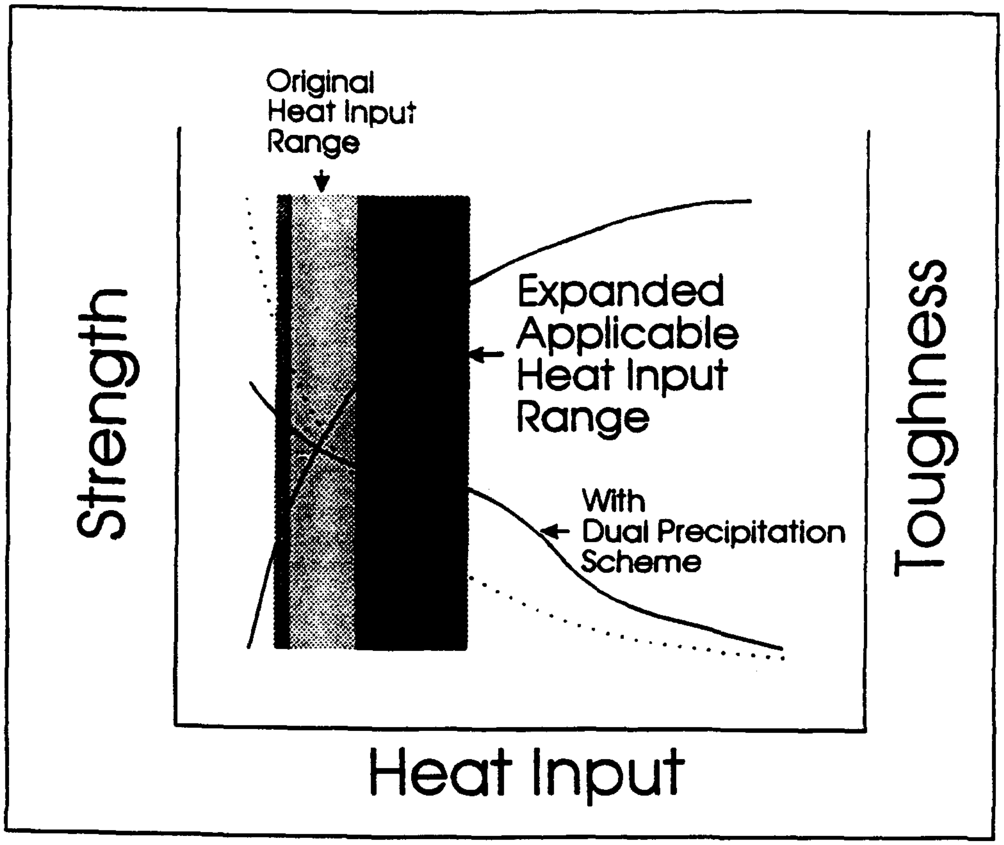


Figure 22. Schematic diagram illustrating the effect of dual precipitation and the broadening of the applicable heat input range.

to a yield strength of 900 MPa, over the extended heat input range (1.2 to 3.6 kJ/mm), during multi-pass welding.

ACKNOWLEDGMENT

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RESEARCH PERSONNEL (1990-1993)

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PROPOSAL FOR MODEL AND FEASIBILITY VERIFICATION

A proposal with research tasks for one year has been submitted to the NSWC-CD to further examine the multi-pass welding aspects of the dual precipitation welds. Instead of the laboratory scale copper and niobium additions, actual welding consumables with copper and niobium additions (produced by a consumables manufacturer) will be used to generate welds for mechanical and impact toughness data. Additionally, the ε-copper and niobium carbide precipitates will be characterized to verify the proposed synergic precipitation model.