Some Observations on the Electron Beam Welding of Copper

Bead-on-plate welds show the effects of impurities, focus position and energy input, and high rates of heat input can retard recrystallization effects

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ABSTRACT. The investigation described in this paper was primarily material oriented. The first portion studied the effects of varying power, focus, travel speed, and slight amounts of impurities in the copper during welding; the second portion studied the effects of varying amounts of coldworking in the base metal and the resultant effect on the heat-affected zone width.

For the initial study all possible combinations of selected parameter levels were used to give 162 bead-on-plate welds in $1/2$ in. material. Three levels each of focus, power, and impurity content in essentially pure copper were used at six different travel speeds. The weld measurements most often made were relative porosity, penetration, and area of the fusion zone. There is a significant difference in penetration between three impurity levels of copper. Penetration is greatest for greatest depth of focus under otherwise constant conditions; porosity also increases with depth of focus. Highest travel speed and beam power give the greatest efficiencies for the process. In order to meaningfully develop mathematical models of electron beam welding, power density must be measured and incorporated in the development.

The second part of the study was to determine if equilibrium metallurgical effects (recrystallization of cold-worked material) would be noticed under the non-equilibrium conditions of electron beam welding, and, if so, how the weld area microstructure would be affected. Both oxygen-free and phosphorus-deoxidized copper were used; the two grades were rolled into $1/8$ in. plates, either fully annealed or cold-rolled to 11% or 75% reduction in thickness. Several combinations of mate-

rial, cold work, focus, and travel speed were used for bead-on-plate welds. It was found that the width of the heat-affected (recrystallized) zone for a high impurity level copper was about $2/3$ that of a low impurity level copper. Rate of heat input strongly influenced the effect of impurities on heat-affected zone width; the higher rates of heat input completely suppressed equilibrium recrystallization and growth.

Introduction

Although the electron beam welding process has found many immediate applications for otherwise difficult or impossible joining problems, relatively little quantitative information has been available concerning machine and material variables affecting welding. As a result, much of current electron beam technology is far from being on a scientific basis. We have been engaged in a research endeavour to better characterize the electron beam process and thus be able to systematically choose materials and parameters without spending excessive time and money in trial and error.

The emphasis of this research program was placed on material effects. Copper was chosen as the first of several common materials to be investigated. While there are many aspects of copper welding that could be studied, this paper is confined to:

1. Fusion zone dimensions as affected by impurity levels and machine variables.

2. Some effects of residual cold work and impurity levels on weld area microstructures.

Main Parameter and Impurity Effects

General

The first part of the program involved 154 bead-on-plate welds in $1/2$ in. thick, 3 in. square coupons. Every combination of 3 power levels, 3 impurity levels, 3 focus positions, and 6 travel speeds was used. These levels were: power—4.0, 5.7, and 6.9 kw, impurities—48, 202, and 359 ppm, focus—$1/4$ in. below surface, on surface, and $1/4$ in. above surface, travel speed—15 to 90 ipm in 15 ipm increments.

The power settings were obtained by changing beam current with a constant 27 kv accelerating voltage. Only sulfur, oxygen, and phosphorus concentrations were measured for our study; other elements were either assumed to have little effect on welding or to be uniformly distributed among the materials. Since the suppliers call the materials OFHC, DLP, and DHP, that nomenclature will be retained (OFHC the lowest impurity level, DHP the highest). The measurements most often made were penetration, area of the fusion zone, and relative porosity.

All welds within a given power level-material group were made in random order; only one operator was used, and all welds within a group were made at one time. Focus height was obtained by maintaining a constant focus current and moving the work up and down with respect to the sharp focus position. These precautions were taken to minimize experimental errors arising from time changes in machine characteristics and operator idiosyncrasies. Most of the welds were made on a commercially-available low voltage 30 kw welding unit; several welds were made later on a commercially-available high voltage 6 kw welding unit for comparison.

Porosity

Relative porosity was measured from radiographs, three for each weld (straight up, and inclined 45 deg. right and left). The radiographs were
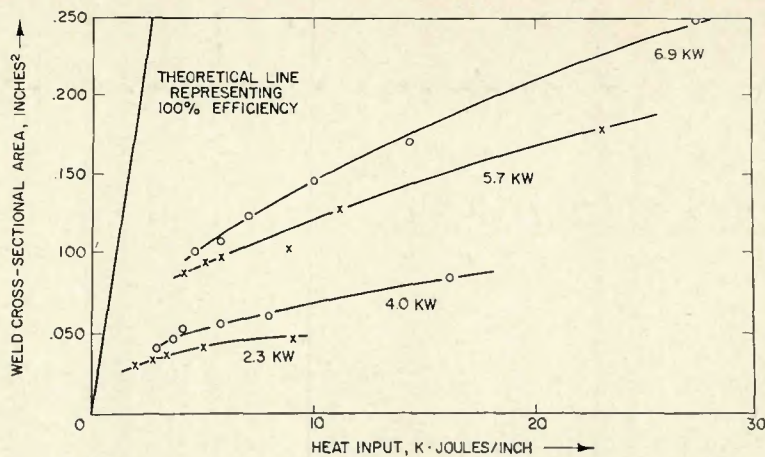
Fig. 1—Weld cross-sectional area vs. heat input. Values averaged over three focus settings. DLP copper, 27 kv

rated by several observers on a 1 (porous) to 5 (sound) basis, and the results were then averaged. While this practice probably introduces some discrepancies, the number of welds involved gives a good indication of any trends in the data. The effect of focus height on porosity was checked by running weld beads along 6 in. coupons in both flat and inclined positions. By maintaining focus current constant while moving along the inclined surface, the effect is the same as continually changing focus current on a flat coupon.

The flat coupon welds allowed determination of the effect of preheating so it could be subtracted in the inclined coupon results. The results verified the initial observations and led to the following conclusions:

1. Porosity increased greatly with increasing power and depth of focus; power has more effect than focus on resultant porosity.

2. Decreasing travel speed also caused a very noticeable increase in porosity. Travel speed, compared to all other single parameters, has the greatest effect on porosity in copper.

3. There was no apparent change in porosity among the three materials.

Metallographic examination showed that most of the porosity resulted from "cold shutting" at the root of the weld. It appeared that molten materi-

al had begun flowing back into a cavity during weld solidification, but it had formed a cold shut before completely filling the void. The remaining porosity was tiny holes scattered throughout the fusion zone; these probably were caused by gas evolution during welding. They did not form a significant portion of the measured porosity.

Fusion Zone Area

A polar planimeter was used to measure fusion zone areas from $\times 10$ photographs of transverse sections of the welds. Preliminary investigation showed that the inaccuracy in the measurements was due almost entirely to variations in the photographic magnifications rather than in the planimeter readings, so the $\pm 3\%$ estimated error in the photographs is a reasonable estimate of total error.

Each given heat input will theoretically melt a certain volume of copper. By assuming a 1 in. length of weld, this volume can be represented as a theoretical cross-sectional area. The heat requirements were calculated from thermodynamic data and represent only the heat needed to raise a given mass of copper from 298° K to the melting temperature (including the heat of fusion); since vaporization, and probably overheating of the vapor. also occurs as well as inevitable

overheating of the liquid, these calculations are not exact. However, there seems to be no way to assign better values for the heat required for welding.

Efficiencies were assigned to each weld by comparing the actual area of the fusion zone with the theoretical area. These efficiencies are typically in the 5–20% range. Thermal conductivity certainly contributes greatly to this deviation from the largest possible area.

Since travel speed is one of the determining factors of heat input, it is possible to plot an entire series of welds at one power level as fusion zone area versus heat input. These plots are shown in Fig. 1. It can be seen that the higher power levels are more efficient than lower power levels. This results in part because large heat inputs cause greater inherent errors in our method of calculating the fusion zone area. There would probably be more vaporization and overheating of the liquid for the larger heat inputs than for smaller heat inputs.

Since travel speed varied, effects such as thermal conductivity, which involves time, will also be different at different heat input levels; unfortunately, the difficulties with a heat flow analysis in welding situations prevents exact quantitative work along these lines. The reader is referred to the literature[1-3] for details of such analysis. At any rate, the high thermal conductivity of copper is quite important to its welding behavior; some preliminary data for titanium show that low thermal conductivity leads to greater efficiency in electron beam welding.

Penetration

Penetration data were also obtained from the photographs. Three sections were cut from each weld and averaged at the start of the program, but it was found that the differences between these sections were rarely 0.02 in. and only occasionally as much as 0.01 in. This finding, plus the large amount of additional time required for metallography, led to the use of only one section from each weld for measurement purposes.

The penetration data were interpreted using Analysis of Variance techniques (ANOVA). The most important numerical results from this analysis are shown in Table 1. The individual sample deviation, $s_x =$ 0.01, was obtained from four welds which were repeated for this purpose. The F-ratio values, obtained by comparing mean square for a particular effect with the residual value, indicate whether a given effect has a truly

Table 1—Analysis of Variance Results and Major Effects

Source of variance	Degrees of freedom	Sum of squares	Mean square	F-ratio
Materials (M)	2	.0176	.0088	88
Power (P)	2	.6757	.3378	3378
Focus	2	.0565	.0282	282
Speed (S)				
Linear	1	.3040	.3040	3040
Quadratic	1	.0158	.0158	158
M x P	4	.0212	.0053	53
P x S	10	.0605	.0061	61
Lack of fit	115	.6434	.0056	56
Residual	7		.0001	

significant effect or is just a chance occurrence during the study. This determination of significance must also take into account the degrees of freedom involved. A high F-ratio coupled with many degrees of freedom indicates a highly significant effect while a low F-ratio and few degrees of freedom represents a minor or insignificant effect.

All linear effects (power, focus, speed, and material), as well as the quadratic dependence of penetration on travel speed, are highly significant. The material-power and power-speed interactions are of secondary significance. The lack of fit term, combining all 3-way and 4-way interactions, is of borderline importance. Since the physical manifestations of 3-way and 4-way interactions are difficult to interpret, they will not be considered here.

Some of the results are plotted in Fig. 2 and 3. Figure 2, showing penetration as a function of travel speed for a particular material, is typical of other power and material curves in that the initial slope is quite steep, but gradually levels out at higher travel speeds. Such a result has been seen by others.[4-6] It should be noted that a given change in travel speed will cause larger variations in the penetration at low travel speeds than at high travel speeds. Figure 3 compares penetration vs. travel speed plots for three power settings. From Table 1 it is seen that the differences in slope of these curves represents a significant interaction between power and travel speed. This means that any functional relationship between penetration and speed will have to have a variable power dependence incorporated in it.

Simple arithmetical averages taken several different ways across the data show focus, material, and power effects that are not obtained from the ANOVA table. These averages are listed in Table 2. The standard deviation is divided by the square root of the number of samples involved to obtain the deviation for an average (denoted by s_x). All of the differences are significant when compared to $2s_x$. It is seen that:

1. Focus below the surface yields greatest penetration.
2. Increasing impurity level causes a decrease in penetration.
3. Penetration is not directly dependent on power level.

The first observation was also reported by Sanderson[7] (among others). The second observation is exactly the opposite of what we had expected. It is fairly well known that increasing amounts of impurities cause thermal conductivity to decrease; con-
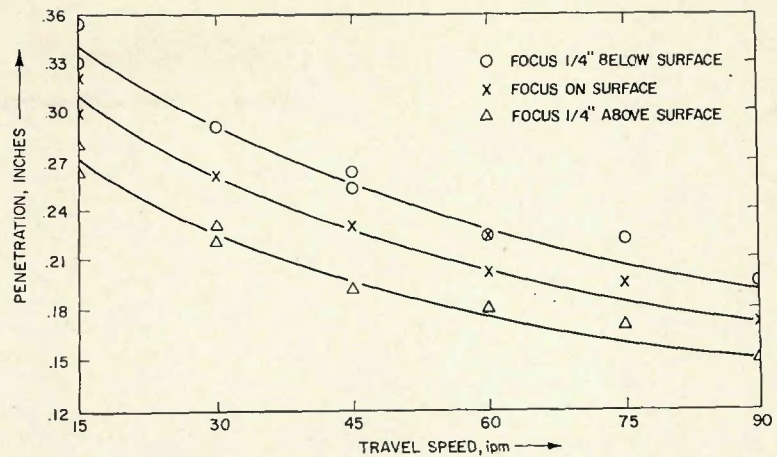

Fig. 2—Penetration vs. travel speed (focus position relative to surface). DLP copper, 27 kv, 210 ma
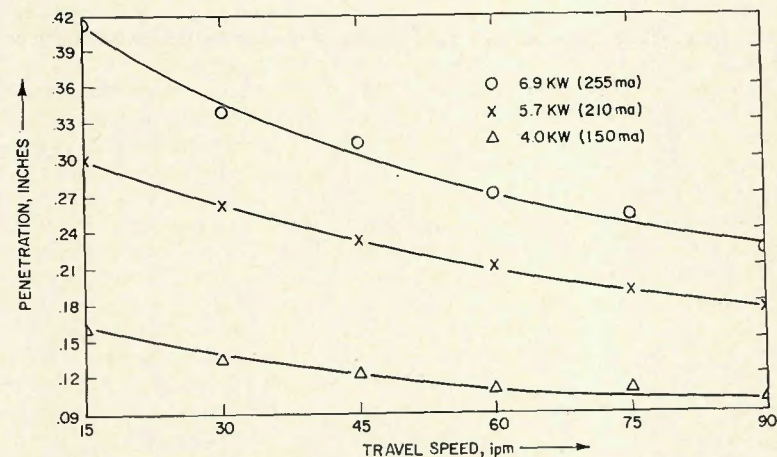

Fig. 3—Penetration vs. travel speed at three power levels. Values averaged over three focus settings. DLP copper, 27 kv

sequently, penetration should increase. This assumption of decreased thermal conductivity with increasing impurity level has not been verified for our materials.

An inquiry concerning measurement of thermal conductivity indicated that experimental error would probably be greater than differences in thermal conductivity among these low impurity level materials. It seems quite possible that vapor pressure caused by the impurities during welding may affect depth of penetration more than slight thermal conductivity variations do. The material-power interaction (Table 1) indicates that this might

be the case. Whatever the reason, the material dependence is real, and although it is slight, it should be considered where accurate work is required.

The third observation, that penetration is not directly dependent on power level, was also seen in Table 1 and Fig. 3. Hashimoto, et al.[5,6] developed mathematical relationships to predict several weld characteristics, such as penetration, from the parameters used to make the weld. These equations were based on experimental results obtained on a 1.5 kw welding unit using accelerating voltages between 30 and 50 kv. His basic equation for penetration was:

Table 2—Penetration Data in Inches—Averaged Over Six Travel Speeds in Each Case

		Focus 1/4 in. above surface	Focus on surface	Focus 1/4 in. below surface	
DHP copper	6.9 kw	0.28	0.30	0.32	Overall average:
	5.7 kw	0.20	0.23	0.25	0.22 in.
	4.0 kw	0.10	0.13	0.14	
DLP copper	6.9 kw	0.28	0.31	0.34	Overall average:
	5.7 kw	0.23	0.25	0.29	0.23 in.
	4.0 kw	0.13	0.13	0.16	
OFHC copper	6.9 kw	0.27	0.30	0.34	Overall average:
	5.7 kw	0.22	0.24	0.26	0.24 in.
	4.0 kw	0.18	0.19	0.17	

$$p = k_a \cdot E^{1.7} \cdot I^{1.0} \cdot \frac{1}{\psi^{0.8}} \qquad (1)$$

where: p = penetration, mm, k_a = material constant, E = accelerating voltage, kv; I = beam current, ma; v = travel speed, cm/min; ψ = beam spot size, mm.

It can be seen that eq (1) is of the form:

$$p = A \cdot X^B \qquad (2)$$

when E and I are assumed constant, and travel speed alone is varied. This simple equation can be fitted to the data very easily in a time-share computer; by merely converting our data to metric units and putting them into a library program, the constants A and B are printed out along with an index of fit.

This equation form consistently has a very high index of fit value when applied to the data. Consequently, the theoretical functional dependence, at least for travel speed, is fairly close to the experimental situation. However, the travel speed exponent decreased as power decreased (from 0.35 to 0.23); this was not predicted in Hashimoto's work. The most logical explanation is the fact that spot size changes with power level. This was not taken into account in the calculations here, because presently there is no good way to measure beam spot size. Spot size largely determines energy density, which is a very important factor in electron beam welding.

A series of welds made at 5.7 kw on the high voltage welding unit was very similar to the 6.9 kw series on the low voltage welding unit (focus and materials being held constant). At first one might think this is conclusive

Table 3—Width of Heat-Affected Zone for Varying Focus Positions, in.[a]

Focus	Travel speed = 20 ipm	Travel speed = 45 ipm
1/2 in. above surface	.390	.125
1/4 in. above surface	.220	.105
On surface	.180	.115
1/4 in. below surface	.190	.115
1/2 in. below surface	.205	.120

[a] 1/8 in. thick DHP copper—75% reduction in thickness—27 kv, 65 ma.

evidence that a high voltage-current ratio is the most effective welding condition; it must be kept in mind, however, that a smaller apparent spot size can be obtained on the high voltage equipment. The differences between the high and low voltage welding units point out again the importance of energy density in electron beam welding. Spot size must be capable of easy measurement in order to control the process. Other workers have also found spot size to be a problem.[2,3]

Optical spot size measurements mean very little, because at higher power levels the "spot" is actually luminous vapors rather than molten material. Although Hashimoto's method of running a plate under the beam gives an indication of spot size, there are some associated problems. Prior experience with this method has given us such varied and ambiguous results that we place little confidence in the system. Secondary electrons were probably at least partly responsible for the discrepancies.

Techniques used by Sanderson[7] and Matting and Sepold[8] to measure focus

position, spot size, and energy density seem very reliable and accurate. A similar technique will be used in later work. This author feels that without some simple, accurate method of measuring the energy density of the beam, electron beam welding technology will remain somewhat akin to "black magic."

Welding of Cold-Worked Material

Background

The second part of the study examined some effects of cold working and impurities in the base metal during welding. Metallurgical investigations[9,10] run under well-controlled laboratory conditions and for much longer times than those involved in welding indicated that relatively small amounts of impurities (about 100 ppm) could greatly reduce recrystallization and growth rates (by a factor of up to 10^{16}). This would consequently raise re-crystallization temperatures as much as several hundred degrees.

Wood[9] determined that oxygen in solid solution, rather than precipitated oxides of other impurities, was the cause of grain growth restraint in high-purity copper. Lucke and Detert,[10] through experimental data and theoretical mathematical models, showed that several impurity elements could inhibit recrystallization and growth. The critical concentration of all these impurities is about 100 ppm; below this concentration the effect is rather small, but above it the rate of recrystallization decreases rapidly with increasing impurity level. This effect was shown to be independent of solubility limits of the any particular im-
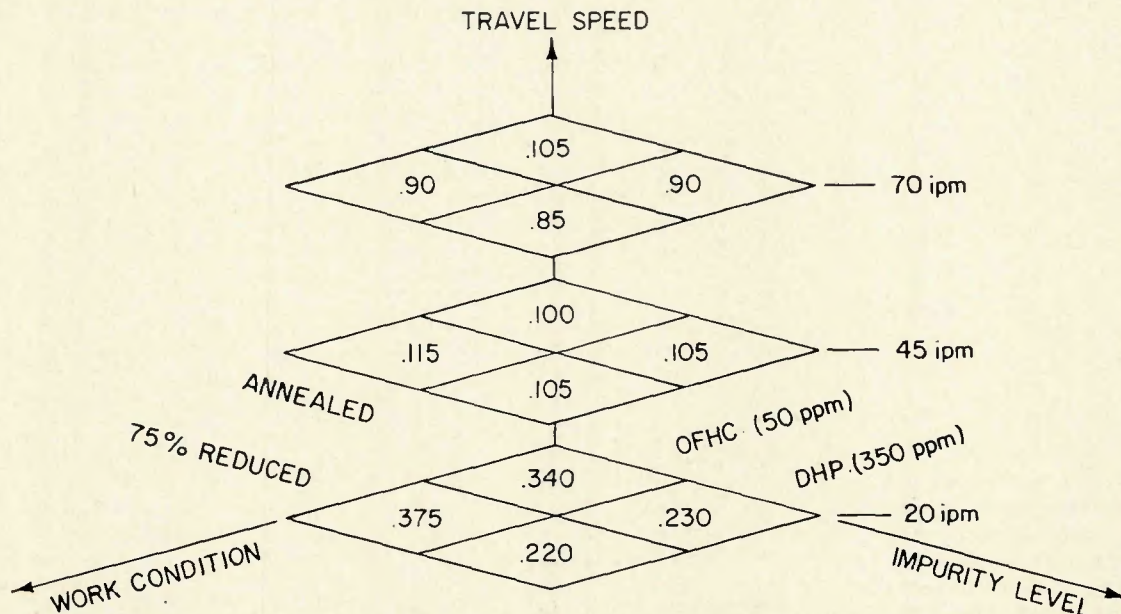

Fig. 4—Results of 2 x 2 x 3 study. Values are width of the heat-affected zone in inches. 27 kv, 65 ma

purity; it was theorized that both elastic (mechanical) and electronic forces are responsible for the pinning effect of impurity atoms on grain boundaries. The breakaway concentration, 100 ppm, is exactly that; grain boundaries are relatively mobile below this.

It is well known that cold working will also affect recrystallization temperatures; some typical curves for tough pitch (ETP) copper have been published.[11] A reduction in thickness of 75% will lower the recrystallization temperature by about 500° F. Of course, time is also an important factor in recrystallization. Since both the impurity effect and degree of cold working data represented long time, quasi-equilibrium studies, we wondered what effects would be noticed for electron beam welding thermal gradients and heating and cooling rates.

Procedure and Results

Two grades of copper (OFHC and DHP) were used for this experiment; the $1/8$ inch coupons were welded in annealed, 11% reduced, and 75% reduced conditions. The impurity levels were chosen to ensure bracketing of the breakaway concentration. The annealing times and temperatures were taken from standard copper rolling practices.

It was found that these procedures eliminated most of the rolling texture, but very little grain growth had occurred. This allowed differentiation between heat-affected and base metal after welding. The extent of the heat-affected (recrystallized) zone was measured to determine the effects of impurities and cold work for several welding conditions. The experiment was divided into three parts:

1. Five welds were made at different focus positions in 75% reduced DHP copper to see what effect a change in power density would have. This set of welds was repeated once at a higher travel speed to see how rate of heat input would affect the results. The parameters and results are shown in Table 3.

2. A series of welds using all combinations of two rolling conditions (annealed and 75% reduced), two materials, and three travel speeds (20, 45, and 70 ipm) was run to determine relative effects of the three variables. The parameters and results are shown in Fig. 4.

3. Three welds were made in DHP coupons with three degrees of cold work to see how much effect cold work alone would have. This set of welds was repeated to give three pairs of data points as an estimate of error. The parameters and results are shown in Table 4.

Table 4—Effect of Cold Work on Width of Heat-Affected Zone, in.[a]

Work condition	Width	Differences from repeated welds
Annealed	.240	
	.205	.35
11% reduced	.195	
	.200	.05
75% reduced	.225	
	.210	.15

[a] $1/8$ in. thick DHP copper—75% reduction—20 ipm, 27 kv, 65 ma.

Discussion

The repeated welds indicate that the standard deviation, s_x, is about 0.016 in. This value reflects primarily the error due to machine, operator, and measurement variation; measurement is probably the greatest single source of error. $2s_x$ was chosen as the criterion for acceptance or rejection of experimental results.

From Fig. 4 it is apparent that the high impurity level greatly inhibits recrystallization and growth; however, this occurs primarily at the low travel speed. The intermediate travel speed shows an effect which is barely significant, and the high travel speed shows no impurity effect at all. This observation contrasts with the findings of Adams,[12] who noticed that, in conventional arc welding, heat cannot be supplied quickly enough to alter equilibrium hardness vs. temperature curves for steel.

The amount of cold work has little or no effect on width of the heat-affected zone as can be seen in Fig. 4 and Table 4. The data of Table 3 show again that a low travel speed is necessary for the impurity effect on heat-affected zone width to be noticeable. Also, defocus above the surface shows a wider heat-affected zone than the corresponding amount of defocus below the surface for the lower travel speed. Since it intuitively seems that the most efficient welding parameters will cause the least amount of heating in the base metal, this observation, (along with penetration measurements made on these samples) supports the previous conclusion that focus below the surface gives the most efficient electron beam welds.

These results show that equilibrium metallurgical observations do not necessarily apply in welding situations such as the electron beam process where temperatures change very rapidly. However, slower travel speeds, with an accompanying increase in heat input, can cause thermal conditions which are more favorable to time-dependent metallurgical phenomena. It seems quite likely that mate-

rials with lower thermal conductivity would not show this same suppression of equilibrium behavior that copper has exhibited, since the meterial in the vicinity of the weld would be at higher temperatures for longer times than would similar regions in a copper weld. It is also probable that conventional arc welding will not suppress equilibrium phenomena to this extent since the high efficiencies and rates of heat input of electron beam welding are not attainable.

Conclusions

1. Porosity in all three grades of copper increased greatly with increasing beam power and depth of focus. Power had a greater effect than depth of focus on resultant porosity.

2. Decreasing travel speed caused a very noticeable increase in porosity. Compared to all other single parameters, travel speed had the greatest effect on porosity in copper.

3. Material impurity level had no apparent effect on porosity in copper.

4. Welds made at higher travel speeds represent greater power efficiency than welds made at low travel speeds. Increasing thermal conductivity causes a decrease in power efficiency.

5. There is an interaction between power and travel speed, implying that any theoretical relationship between penetration and speed will need a variable power dependence term. Penetration is not directly dependent on power level.

6. Penetration increases as the optical focus position moves from $1/4$ in. above the surface of the workpiece to $1/4$ inch below the surface.

7. Increasing impurity level in copper causes a decrease in penetration.

8. Beam spot size (energy density) is a very important parameter in electron beam welding. It is important that it be monitored quickly and accurately.

9. The impurity level in copper affects the width of the heat-affected zone more than does the degree of cold working in the base metal. This is to say that slight amounts of impurities in cold-rolled copper exert more control over recrystallization and growth than does the stored energy of cold working.

10. The recrystallization-growth inhibiting effects of high impurity level are most pronounced at low travel speeds.

11. The high rates of heat input at high travel speeds in electron beam welding make it possible to retard recrystallization and growth phenomena in copper.

Shuler for doing the welding and much of the associated laboratory work. Thanks are also due to Mr. J. Lynch who helped with the statistical analysis of the data.

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Technical Note

P.M.; the SWAT system was activated at 4:41 P.M. Figure 2 is a schematic of the system. With 100X amplification follwed by a 30 kc high-pass filter and then 1000X amplification, a 38 kc input signal (approximately resonance frequency of mounted accelerometer) is amplified 5000X.

In the counter system, two levels of stress-wave amplitude were recorded. The counter stripchart printout recorded cumulative count and count rate (number/minute). By a voltage setting, the count-rate printout was adjusted to read signals just above the background noise level. The cumulative count was set to record the larger stress waves, approximately 5X those of the count-rate printout.

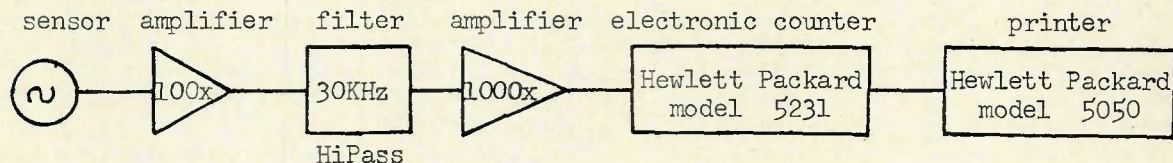Fig. 2—Schematic representation of the SWAT system

Table 1—Delayed Cracking in Welded HY-80 Steel

Date	Time of Signal — Clock time	Stress-wave emission — Cumulative count[a]	Stress-wave emission — Count per minute[b]	Date	Time of Signal — Clock time	Stress-wave emission — Cumulative count[a]	Stress-wave emission — Count per minute[b]	Date	Time of Signal — Clock time	Stress-wave emission — Cumulative count[a]	Stress-wave emission — Count per minute[b]
3 Apr '69	02:25 PM	(Started welding)			34		17		37		8
	03:40	(Welding completed)			35	4567	1146		55		1
	04:40	(Started counter)			37	5539	3751		07:09	7040	22
	49	0	5		38		27		21	7078	125
	50		10		39	5932	1324		22		89
	51	2	437		40	5955	116		08:11		2
	52		6		42		33		24		1
	56		1		46		18		09:01		1
	58	16	925		48		47		59		44
	05:04		3		52	5955			10:45		76
	07	978	2239		53	6346	1581		11:48		129
	10		28		58		38	4 Apr '69	00:23 AM		90
	14		27		06:00		20		24		8
	15		4		02		2		37	7082	518
	16				04	6998	2166		45		49
	19		20		05	7008	1225		01:03		164
	21		17		07		13		03:03		75
	23		40		08	7030	123		04	7107	176
	24		11		09		8		07:41		446
	26		3		20		10		06:53 PM		18
	29	2372	4550		29		2	5 Apr '69	00:15 AM		25
	30		8		31		2		07:19 PM		1
	31	3492	3912		33	7036	35		20	7108[c]	37
	33	4322	2975		34	7039	16	6 Apr '69	—	—	—
								7 Apr '69	07:30 AM	System off	

[a] Counter triggered at 1.0 volt.
[b] Triggered at 0.25 volt.
[c] Corrected to eliminate system check-out signals.