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Volume 6
Welding, Brazing, and Soldering

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Fundamentals of Welding

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Energy Sources Used for Fusion Welding

Thomas W. Eagar, Massachusetts Institute of Technology

WELDING AND JOINING processes are essential for the development of virtually every manufactured product. However, these processes often appear to consume greater fractions of the product cost and to create more of the production difficulties than might be expected. There are a number of reasons that explain this situation.

First, welding and joining are multifaceted, both in terms of process variations (such as fastening, adhesive bonding, soldering, brazing, arc welding, diffusion bonding, and resistance welding) and in the disciplines needed for problem solving (such as mechanics, materials science, physics, chemistry, and electronics). An engineer with unusually broad and deep training is required to bring these disciplines together and to apply them effectively to a variety of processes.

Second, welding or joining difficulties usually occur far into the manufacturing process, where the relative value of scrapped parts is high.

Third, a very large percentage of product failures occur at joints because they are usually located at the highest stress points of an assembly and are therefore the weakest parts of that assembly. Careful attention to the joining processes can produce great rewards in manufacturing economy and product reliability.

The Section "Fusion Welding Processes" in this Volume provides details about equipment and systems for the major fusion welding processes. The purpose of this Section of the Volume is to discuss the fundamentals of fusion welding processes, with an emphasis on the underlying scientific principles.

Because there are many fusion welding processes, one of the greatest difficulties for the manufacturing engineer is to determine which process will produce acceptable properties at the lowest cost. There are no simple answers. Any change in the part geometry, material, value of the end product, or size of the production run, as well as the availability of joining equipment, can influence the choice of joining method. For small lots of complex parts, fastening may be preferable to welding, whereas for long production runs, welds can be stronger and less expensive.

The perfect joint is indistinguishable from the material surrounding it. Although some processes, such as diffusion bonding, can achieve results that are very close to this ideal, they are either expensive or restricted to use with just a few materials. There is no universal process that performs adequately on all materials in all geometries. Nevertheless, virtually any material can be joined in some way, although joint properties equal to those of the bulk material cannot always be achieved.

The economics of joining a material may limit its usefulness. For example, aluminum is used extensively in aircraft manufacturing and can be joined by using adhesives or fasteners, or by welding. However, none of these processes has proven economical enough to allow the extensive replacement of steel by aluminum in the frames of automobiles. An increased use of composites in aircrafts is limited by an inability to achieve adequate joint strength.

It is essential that the manufacturing engineer work with the designer from the point of product conception to ensure that compatible materials, processes, and properties are selected for the final assembly. Often, the designer leaves the problem of joining the parts to the manufacturing engineer. This can cause an escalation in cost and a decrease in reliability. If the design has been planned carefully and the parts have been produced accurately, the joining process becomes much easier and cheaper, and both the quality and reliability of the product are enhanced.

Generally, any two solids will bond if their surfaces are brought into intimate contact. One factor that generally inhibits this contact is surface contamination. Any freshly produced surface exposed to the atmosphere will absorb oxygen, water vapor, carbon dioxide, and hydrocarbons very rapidly. If it is assumed that each molecule that hits the surface will be absorbed, then the time-pressure value to produce a monolayer of contamination is approximately 0.001 Pa · s (10^{-8} atm · s). For example, at a pressure of 1 Pa (10^{-5} atm), the contamination time is 10^{-3} s, whereas at 0.1 MPa (1 atm), it is only 10×10^{-9} s.

In fusion welding, intimate interfacial contact is achieved by interposing a liquid of substantially similar composition as the base metal. If the surface contamination is soluble, then it is dissolved in the liquid. If it is insoluble, then it will float away from the liquid-solid interface.

Energy-Source Intensity

One distinguishing feature of all fusion welding processes is the intensity of the heat source used to melt the liquid. Virtually every concentrated heat source has been applied to the welding process. However, many of the characteristics of each type of heat source are determined by its intensity. For example, when considering a planar heat source diffusing into a very thick slab, the surface temperature will be a function of both the surface power density and the time.

Figure 1 shows how this temperature will vary on steel with power densities that range from 400 to 8000 W/cm^2. At the lower value, it takes 2 min to melt the surface. If that heat source were a point on the flat surface, then the heat flow would be divergent and might not melt the steel. Rather, the solid metal would be able to conduct away the heat as fast as it was being introduced. It is generally found that heat-source power densities of approximately 1000 W/cm^2 are necessary to melt most metals.

At the other end of the power-density spectrum, heat intensities of 10^6 or 10^7 W/cm^2 will vaporize most metals within a few microseconds. At levels above these values, all of the solid that interacts with the heat source will be vaporized, and no fusion welding can occur. Thus, the heat sources for all fusion welding processes should have power densities between approximately 0.001 and 1 MW/cm^2. This

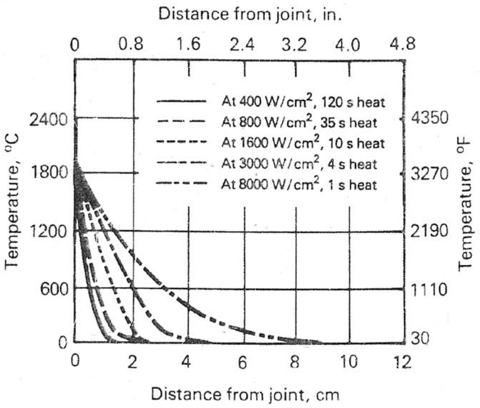

Fig. 1 Temperature distribution after a specific heating time in a thick steel plate heated uniformly on one surface as a function of applied heat intensity; initial temperature of plate is 25 °C (77 °F)

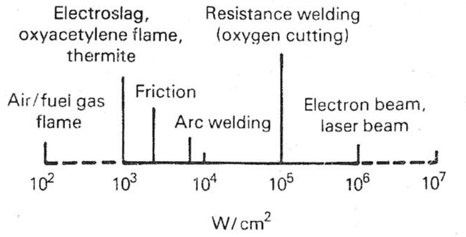

Fig. 2 Spectrum of practical heat intensities used for fusion welding

Table 1 Thermal diffusivities of common elements from 20 to 100 °C (68 to 212 °F)

	Density		Heat capacity		Thermal conductivity		Thermal diffusivity	
Element	g/cm^3	lb/in.^{3}	J/kg · K	cal$_{IT}$/g · °C	W/m · K	cal$_{IT}$/cm · s · °C	mm^2/s	cm^2/s
Aluminum	2.699	0.098	900	0.215	221	0.53	91	0.91
Antimony	6.62	0.239	205	0.049	19	0.045	14	0.14
Beryllium	1.848	0.067	1880	0.45	147	0.35	42	0.42
Bismuth	9.80	0.354	123	0.0294	8	0.020	7	0.069
Cadmium	8.65	0.313	230	0.055	92	0.22	46	0.46
Carbon	2.25	0.081	691	0.165	24	0.057	15	0.15
Cobalt	8.85	0.320	414	0.099	69	0.165	19	0.188
Copper	8.96	0.324	385	0.092	394	0.941	114	1.14
Gallium	5.907	0.213	331	0.079	29–38	0.07–0.09	17	0.17
Germanium	5.323	0.192	306	0.073	59	0.14	36	0.36
Gold	19.32	0.698	131	0.0312	297	0.71	118	1.178
Hafnium	13.09	0.472	147	0.0351	22	0.053	12	0.12
Indium	7.31	0.264	239	0.057	24	0.057	14	0.137
Iridium	22.5	0.813	129	0.0307	59	0.14	20	0.20
Iron	7.87	0.284	460	0.11	75	0.18	21	0.208
Lead	11.36	0.410	129	0.0309	35	0.083	24	0.236
Magnesium	1.74	0.063	1025	0.245	154	0.367	86	0.86
Molybdenum	10.22	0.369	276	0.066	142	0.34	50	0.50
Nickel	8.902	0.322	440	0.105	92	0.22	23.5	0.235
Niobium	8.57	0.310	268	0.064	54	0.129	23.6	0.236
Palladium	12.02	0.434	244	0.0584	70	0.168	24	0.24
Platinum	21.45	0.775	131	0.0314	69	0.165	24.5	0.245
Plutonium	19.84	0.717	138	0.033	8	0.020	3.0	0.030
Rhodium	12.44	0.449	247	0.059	88	0.21	29	0.286
Silicon	2.33	0.084	678	0.162	84	0.20	53	0.53
Silver	10.49	0.379	234	0.0559	418	1.0	170	1.705
Sodium	0.9712	0.035	1235	0.295	134	0.32	112	1.12
Tantalum	16.6	0.600	142	0.034	54	0.130	23	0.23
Tin	7.2984	0.264	226	0.054	63	0.150	38	0.38
Titanium	4.507	0.163	519	0.124	22	0.052	9	0.092
Tungsten	19.3	0.697	138	0.033	166	0.397	62	0.62
Uranium	19.07	0.689	117	0.0279	30	0.071	13	0.13
Vanadium	6.1	0.22	498	0.119	31	0.074	10	0.10
Zinc	7.133	0.258	383	0.0915	113	0.27	41	0.41
Zirconium	6.489	0.234	280	0.067	21	0.050	12	0.12

Table 2 Thermal diffusivities of common alloys from 20 to 100 °C (68 to 212 °F)

	Density		Heat capacity		Thermal conductivity		Thermal diffusivity	
Alloys	g/cm^3	lb/in.^{3}	J/kg · K	cal$_{IT}$/g · °C	W/m · K	cal$_{IT}$/cm · s · °C	mm^2/s	cm^2/s
Aluminum alloys								
1100	2.71	0.098	963	0.23	222	0.53	85	0.85
2014	2.80	0.101	963	0.23	193	0.46	71	0.71
5052	2.68	0.097	963	0.23	138	0.33	54	0.54
6061	2.70	0.098	963	0.23	172	0.41	66	0.66
7075	2.80	0.101	963	0.23	121	0.29	45	0.45
Copper alloys								
Commercial bronze	8.80	0.318	377	0.09	188	0.45	57	0.57
Cartridge brass	8.53	0.308	377	0.09	121	0.29	38	0.38
Naval brass	8.41	0.303	377	0.09	117	0.28	37	0.37
Beryllium copper	8.23	0.297	419	0.1	84	0.20	24	0.24
9% aluminum bronze	7.58	0.273	435	0.104	60	0.144	18	0.18
Magnesium alloys								
AZ 31	1.78	0.064	1050	0.25	84	0.20	45	0.45
AZ 91	1.83	0.066	1005	0.24	84	0.20	46	0.46
ZW 1	1.8	0.065	1005	0.24	134	0.32	74	0.74
RZ 5	1.84	0.066	963	0.23	113	0.27	64	0.64
Stainless steels								
Type 301	7.9	0.285	502	0.12	16	0.039	4.1	0.041
Type 304	7.9	0.285	502	0.12	15.1	0.036	3.8	0.038
Type 316	8.0	0.289	502	0.12	15.5	0.037	3.9	0.039
Type 410	7.7	0.278	460	0.11	24	0.057	6.7	0.067
Type 430	7.7	0.278	460	0.11	26	0.062	7.3	0.073
Type 501	7.7	0.278	460	0.11	37	0.088	10	0.10
Nickel-base alloys								
Nimonic 80A	8.19	0.296	460	0.11	11	0.027	3.0	0.030
Inconel 600	8.42	0.304	460	0.11	15	0.035	3.8	0.038
Monel 400	8.83	0.319	419	0.10	22	0.052	5.8	0.058
Titanium alloys								
Ti-6A1-4V	4.43	0.160	611	0.146	5.9	0.014	2.1	0.021
Ti-5A1-2.5Sn	4.46	0.161	460	0.11	6.3	0.015	3.1	0.031

power-density spectrum is shown in Fig. 2, along with the points at which common joining processes are employed.

The fact that power density is inversely related to the interaction time of the heat source on the material is evident in Fig. 1. Because this represents a transient heat conduction problem, one can expect the heat to diffuse into the steel to a depth that increases as the square root of time, that is, from the Einstein equation:

$$x \sim \sqrt{\alpha t} \qquad \text{(Eq 1)}$$

where x is the distance that the heat diffuses into the solid, in centimeters; α is the thermal diffusivity of the solid, in cm^2/s; and t is the time in seconds. Tables 1 and 2 give the thermal diffusivities of common elements and common alloys, respectively.

For the planar heat source on a steel surface, as represented by Fig. 1, the time in seconds to produce melting on the surface, t_m, is given by:

$$t_m = (5000/\text{H.I.})^2 \qquad \text{(Eq 2)}$$

where H.I. is the net heat intensity (in W/cm^2) transferred to the workpiece.

Equation 2 provides a rough estimate of the time required to produce melting, and is based upon the thermal diffusivity of steel. Materials with higher thermal diffusivities—or the use of a local point heat source rather than a planar heat source—will increase the time to produce melt-

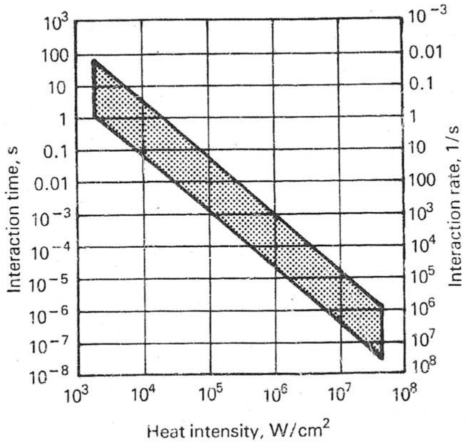

Fig. 3 Typical weld pool-heat source interaction times as function of heat-source intensity. Materials with a high thermal diffusivity, such as copper or aluminum, would lie near the top of this band, whereas steels, nickel alloys, or titanium would lie in the middle. Uranium and ceramics, with very low thermal diffusivities, would lie near the bottom of the band.

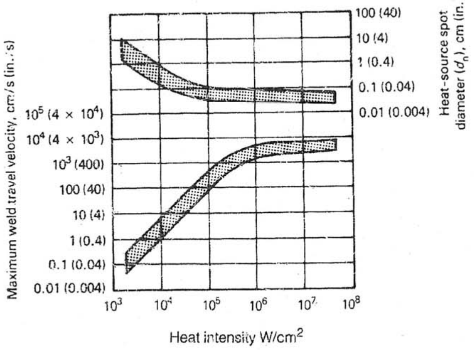

Fig. 4 Maximum weld travel velocity as a function of heat-source intensity based on typical heat-source spot diameters

ing by a factor of up to two to five times. On the other hand, thin materials tend to heat more quickly.

If the time to melting is considered to be a characteristic interaction time, t_I, then the graph shown in Fig. 3 can be generated. Heat sources with power densities that are of the order of 1000 W/cm^2, such as oxyacetylene flames or electroslag welding, require interaction times of 25 s with steel, whereas laser and electron beams, at 1 MW/cm^2, need interaction times on the order of only 25 μs. If this interaction time is divided into the heat-source diameter, d_H, then a maximum travel speed, V_{max}, is obtained for the welding process (Fig. 4).

The reason why welders begin their training with the oxyacetylene process should be clear: it is inherently slow and does not require rapid response time in order to control the size of the weld puddle. Greater skill is needed to control the more-rapid fluctuations in arc processes. The

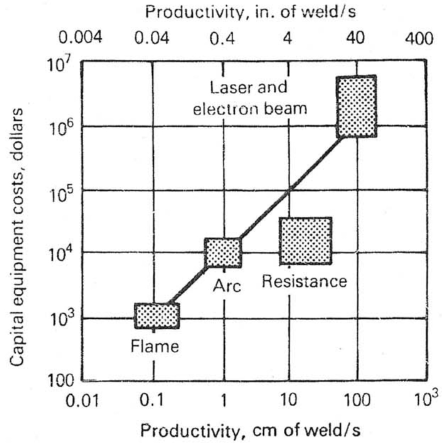

Fig. 5 Approximate relationship between capital cost of welding equipment and speed at which sheet metal joints can be produced

weld pool created by the high-heat-intensity processes, such as laser-beam and electron-beam welding, cannot be humanly controlled and must therefore be automated. This need to automate leads to increased capital costs. On an approximate basis, the W/cm^2 of a process can be substituted with the dollar cost of the capital equipment. With reference to Fig. 2, the cost of oxyacetylene welding equipment is nearly \$1000, whereas a fully automated laser-beam or electron-beam system can cost \$1 million. Note that the capital cost includes only the energy source, control system, fixturing, and materials handling equipment. It does not include operating maintenance or inspection costs, which can vary widely depending on the specific application.

For constant total power, a decrease in the spot size will produce a squared increase in the heat intensity. This is one of the reasons why the spot size decreases with increasing heat intensity (Fig. 4). It is easier to make the spot smaller than it is to increase the power rating of the equipment. In addition, only a small volume of material usually needs to be melted. If the spot size were kept constant and the input power were squared in order to obtain higher densities, then the volume of fused metal would increase dramatically, with no beneficial effect.

However, a decreasing spot size, coupled with a decreased interaction time at higher power densities, compounds the problem of controlling the higher-heat-intensity process. A shorter interaction time means that the sensors and controllers necessary for automation must operate at higher frequencies. The smaller spot size means that the positioning of the heat source must be even more precise, that is, on the order of the heat-source diameter, d_H. The control frequency must be greater than the travel velocity divided by the diameter of the heat source. For processes that operate near the maximum travel velocity, this is

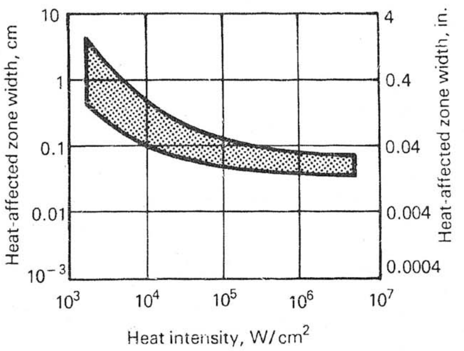

Fig. 6 Range of weld HAZ widths as function of heat-source intensity

the inverse of the process interaction time, t_I (Fig. 3).

Thus, not only must the high-heat-intensity processes be automated because of an inherently high travel speed, but the fixturing requirements become greater, and the control systems and sensors must have ever-higher frequency responses. These factors lead to increased costs, which is one reason that the very productive laser-beam and electron-beam welding processes have not found wider use. The approximate productivity of selected welding processes, expressed as length of weld produced per second, to the relative capital cost of equipment is shown in Fig. 5.

Another important welding process parameter that is related to the power density of the heat source is the width of the heat-affected zone (HAZ). This zone is adjacent to the weld metal and is not melted itself but is structurally changed because of the heat of welding. Using the Einstein equation, the HAZ width can be estimated from the process interaction time and the thermal diffusivity of the material. This is shown in Fig. 6, with one slight modification. At levels above approximately 10^4 W/cm^2, the HAZ width becomes roughly constant. This is due to the fact that the HAZ grows during the heating stage at power densities that are below 10^4 W/cm^2, but at higher power densities it grows during the cooling cycle. Thus, at low power densities, the HAZ width is controlled by the interaction time, whereas at high power densities, it is independent of the heat-source interaction time. In the latter case, the HAZ width grows during the cooling cycle as the heat of fusion is removed from the weld metal, and is proportional to the fusion zone width.

The change of slope in Fig. 6 also represents the heat intensity at which the heat utilization efficiency of the process changes. At high heat intensities, nearly all of the heat is used to melt the material and little is wasted in preheating the surroundings. As heat intensity decreases, this efficiency is reduced. For arc welding, as little as half of the heat generated may enter the plate, and only 40% of this heat is used to fuse the metal. For oxyacetylene welding, the heat entering the metal may be 10% or less of the total heat, and the heat necessary to fuse the metal may be less than 2% of the total heat.

A final point is that the heat intensity also controls the depth-to-width ratio of the molten pool. This value can vary from 0.1 in low-heat-intensity processes to more than 10 in high-heat-intensity processes.

It should now be evident that all fusion welding processes can be characterized generally by heat-source intensity. The properties of any new heat source can be estimated readily from the figures in this article. Nonetheless, it is useful to more fully understand each of the common welding heat sources, such as flames, arcs, laser beams, electron beams, and electrical resistance. These are described in separate articles in the Section "Fusion Welding Processes" in this Volume.