

Welding Process Fundamentals*

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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 may 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 weldment design and joining processes can produce great rewards in manufacturing economy and product reliability.

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 nonluxury automobiles. An increased use of composites in aircrafts is limited by an inability to achieve adequate joint strength in the original product or to repair a product that has been in service.

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 $0.001 \text{ Pa} \cdot \text{s}$ ($10^{-8} \text{ atm} \cdot \text{s}$). 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 $10 \times 10^{-9} \text{ s}$ (Ref 1).

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 create the molten condition. 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 less than a minute to melt the surface. If that heat source were a point on the flat surface, as shown in Fig. 2, then the heat flow would be divergent and not melt the steel. This shows the dramatic effect of divergent heat flow and the need for higher heat intensities when the heat source is a laser, an arc, or a point source compared to a planar heat source as developed in friction welding. Rather, the solid metal would be able to conduct away the heat as fast as it was being introduced. It is generally found that point heat-source power densities of approximately 1000 W/cm^2 are necessary to melt most metals.

* Updated and revised from T.W. Eagar, Energy Sources Used for Fusion Welding, *Welding, Brazing, and Soldering*, Vol 6, *ASM Handbook*, ASM International, 1993.

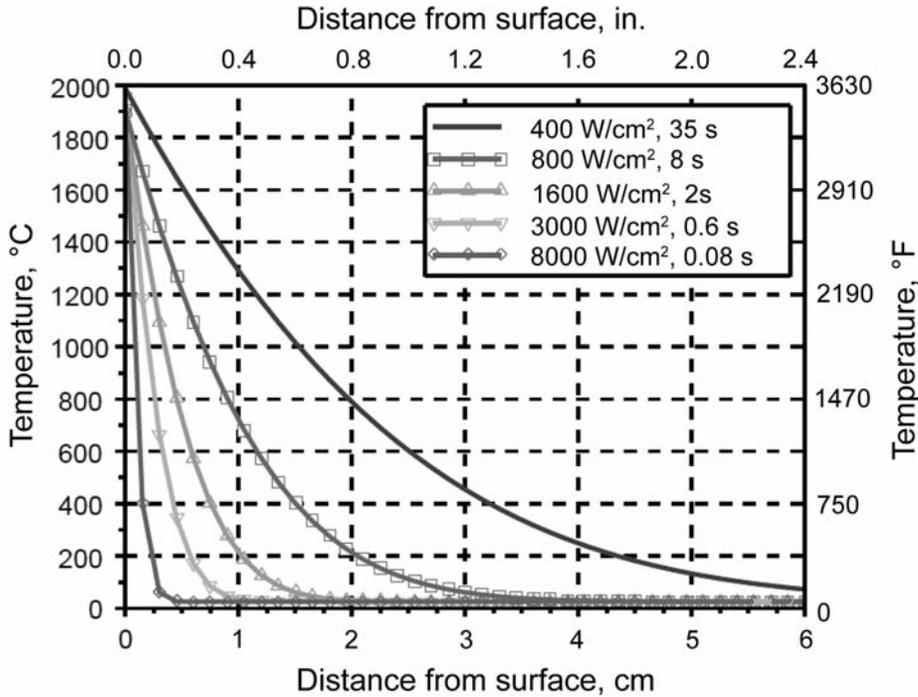


Fig. 1 Temperature distribution after a specific heating time in a thick steel plate heated uniformly on one surface as a function of applied heat intensity. Initial temperature of plate is 25 °C (77 °F), thermal conductivity is 50 W/m · K, specific heat capacity is 475 J/kg · K, density is 7800 kg/m³ (0.28 lb/in.³), and thermal diffusivity is 0.13 cm²/s.

At the other end of the power-density spectrum, heat intensities of 10⁶ or 10⁷ W/cm² 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 (resulting in hole drilling), 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/cm². This power-density spectrum is shown in Fig. 3, along with the points at which common joining processes are employed (Ref 2, 3).

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:

$$x \sim \sqrt{\alpha t} \tag{Eq 1}$$

where x is the distance that the heat diffuses into the solid, in centimeters; α is the thermal diffusivity of the solid, in cm²/s; and t is the time in seconds. Tables 1 and 2 give the thermal diffusivities of common elements and common alloys, respectively. In addition, Table 3 shows how thermal diffusivity of materials can vary with temperature.

For the planar heat source on a steel surface, as represented by Fig. 1 and 4, the time in

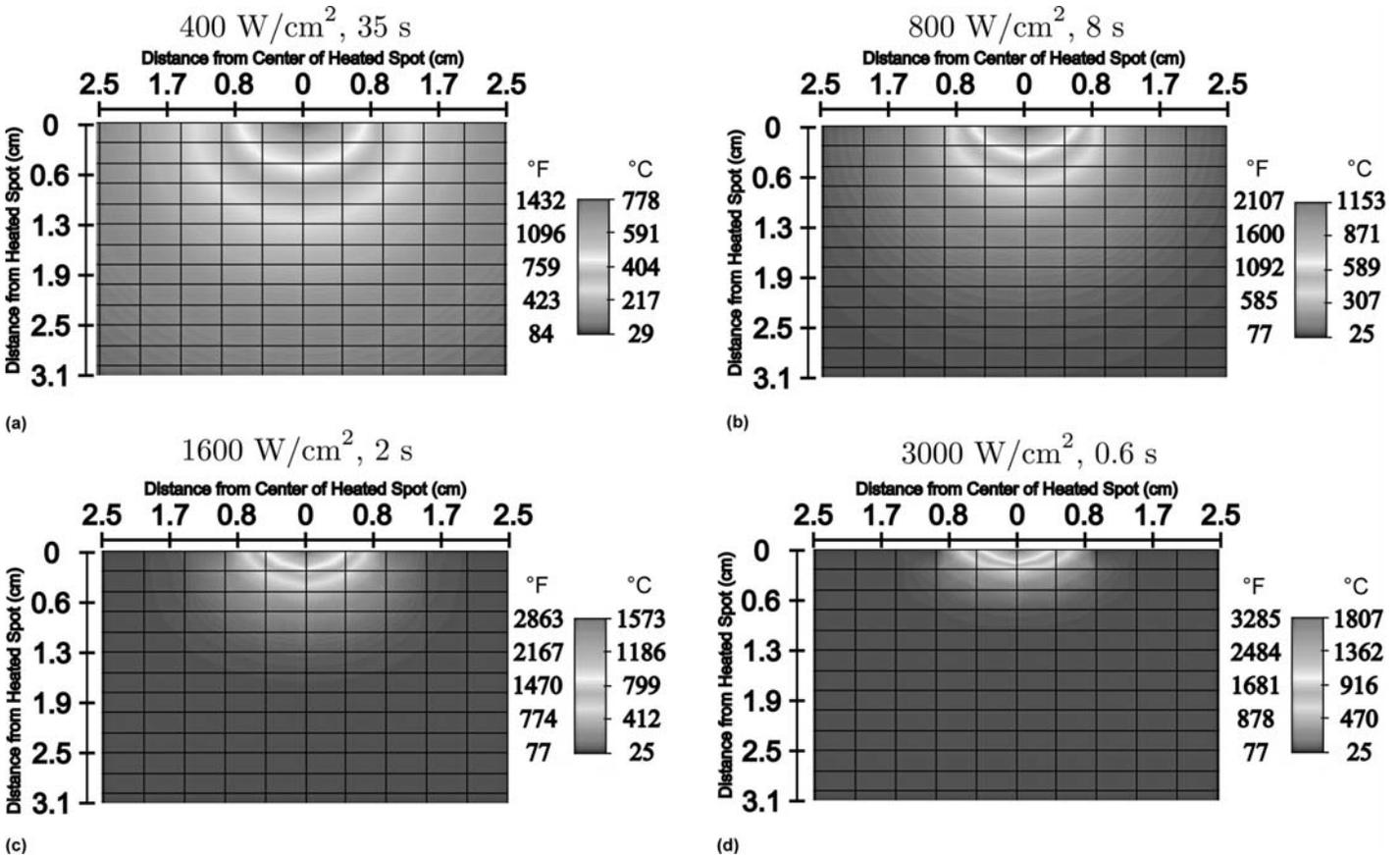


Fig. 2 Finite-element analysis temperature distribution results after a specific heating time in a thick steel plate heated over a 1 cm (0.4 in.) wide region on the top surface. Initial temperature of plate is 25 °C (77 °F), thermal conductivity is 50 W/m · K, specific heat capacity is 475 J/kg · K, density is 7800 kg/m³ (0.28 lb/in.³), and thermal diffusivity is 0.13 cm²/s. Images are magnified views of a 6.25 cm tall by 10 cm wide (2.5 in. tall by 4.0 in. wide) cross section.

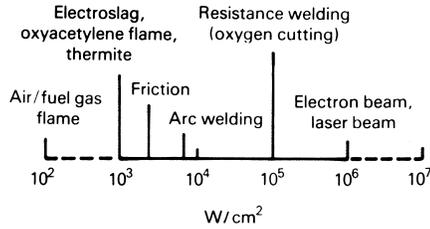


Fig. 3 Spectrum of practical heat intensities used for fusion welding

seconds for the heated surface temperature to increase by an amount ΔT is given by:

$$t = \pi k^2 (\Delta T)^2 / [4\alpha (H.I.)^2 \times 10^4] \quad (\text{Eq 2})$$

where H.I. is the net heat intensity (in W/cm^2) transferred to the workpiece, k is the thermal conductivity (in $\text{W}/\text{m} \cdot \text{K}$) of the material, and α is the thermal diffusivity of the material (in cm^2/s) (Ref 8). The time in seconds to produce melting on the surface, t_m , is given by:

$$t_m = (1800/\text{H.I.})^2 \quad (\text{Eq 3})$$

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

Equation 3 provides a rough estimate of the time required to produce melting and is based on the thermal diffusivity of steel. Materials with higher thermal diffusivities—or the use of a local point heat source (with divergence of heat flux) rather than a planar heat source—will increase the time to produce melting by a factor of up to 2 to 5 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. 5 can be generated. Heat sources with power densities that are of the order of $1000 \text{ W}/\text{cm}^2$, such as oxyacetylene flames or electroslag welding, require interaction times on the order of 1 s with steel, whereas laser and electron beams, at $1 \text{ MW}/\text{cm}^2$, need interaction times on the order of only $1 \mu\text{s}$. 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. 6).

The reason why welders begin their training with the oxyacetylene process should be clear: this process is inherently slow and does not require rapid response time to control the size of the weld puddle. Greater skill is needed to control the more-rapid fluctuations in arc processes, where the reaction time required is less than a second. The 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 heat intensity in W/cm^2 of a process can be substituted

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

Element	Density		Heat capacity		Thermal conductivity		Thermal diffusivity	
	g/cm^3	$\text{lb}/\text{in.}^3$	$\text{J}/\text{kg} \cdot \text{K}$	$\text{cal}/\text{g} \cdot ^\circ\text{C}$	$\text{W}/\text{m} \cdot \text{K}$	$\text{cal}/\text{cm} \cdot \text{s} \cdot ^\circ\text{C}$	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)

Material names	Density		Heat capacity		Thermal conductivity		Thermal diffusivity		Ref
	g/cm^3	$\text{lb}/\text{in.}^3$	$\text{J}/\text{kg} \cdot \text{K}$	$\text{cal}/\text{g} \cdot ^\circ\text{C}$	$\text{W}/\text{m} \cdot \text{K}$	$\text{cal}/\text{cm} \cdot \text{s} \cdot ^\circ\text{C}$	mm^2/s	cm^2/s	
Aluminum alloys									
1100 O temper	2.71	0.098	904	0.22	222	0.53	90.62	0.91	4
6061 O temper	2.7	0.098	896	0.21	180	0.43	74.4	0.74	4
7075 T6 temper	2.8	0.101	960	0.23	130	0.31	48.36	0.48	4
Copper alloys									
C22000 commercial bronze	8.8	0.318	376	0.09	189	0.45	57.12	0.57	4
C26000 cartridge brass	8.53	0.308	375	0.09	120	0.29	37.51	0.38	4
C46400 naval brass	8.41	0.304	380	0.09	116	0.28	36.3	0.36	4
C17000 beryllium copper	8.26	0.298	420	0.1	118	0.28	34.01	0.34	4
C60600 aluminum bronze	8.17	0.295	375	0.09	79.5	0.19	25.95	0.26	4
Magnesium alloys									
AZ61A	1.8	0.065	1050	0.25	80	0.19	42.33	0.42	4
AZ91	1.81	0.065	1050	0.25	72	0.17	37.88	0.38	4
Carbon steels									
AISI 1025	7.86	0.284	486	0.12	51.1	0.12	13.38	0.13	5, 6
Iron, carbon steel, 0.5% C	7.83	0.283	465	0.11	54	0.13	14.83	0.15	7
Iron, carbon steel, 1.0% C	7.8	0.282	473	0.11	43	0.1	11.65	0.12	7
Iron, carbon steel, 1.5% C	7.75	0.280	486	0.12	36	0.09	9.55	0.1	7
Stainless steels									
Type 301	8	0.289	500	0.12	16.2	0.04	4.05	0.04	5
Type 304	7.82	0.282	460	0.11	13.8	0.04	3.84	0.04	7
Type 316	8	0.289	500	0.12	16.2	0.04	4.05	0.04	5
Type 347	7.82	0.282	420	0.1	15	0.04	4.57	0.05	7
Type 410	7.8	0.282	460	0.11	24.9	0.06	6.94	0.07	5
Nickel-base alloys									
Nimonic 80A	8.16	0.295	460	0.11	8.7	0.02	2.32	0.02	5
Inconel 600	8.41	0.304	445	0.11	14.8	0.04	3.95	0.04	5
Titanium alloys									
6Al-4V	4.43	0.160	550	0.13	6.7	0.02	2.75	0.03	4, 6
Ti 5Al-2.5Sn	4.48	0.162	530	0.13	6.6	0.02	2.78	0.03	4, 6

Table 3 Temperature effects on thermal diffusivity

Material name	Density		Temperature		Heat capacity		Thermal conductivity		Estimated thermal diffusivity		Ref					
	g/cm ³	lb/in. ³	°C	°F	J/kg · K	cal/g · °C	W/m · K	cal/cm · s · °C	mm ² /s	cm ² /s						
Stainless steels																
Type 304	7.82	0.28	20	68	460	0.12	13.8	0.03	3.8	0.038	7					
			100	212								15	0.04	4.2	0.042	7
			200	390								17	0.04	4.7	0.047	7
			400	750								21	0.05	5.8	0.058	7
			600	1110								25	0.06	7.0	0.070	7
Type 347	7.82	0.28	20	68	420	0.10	15	0.04	4.6	0.046	7					
			100	212								16	0.04	4.9	0.049	7
			200	390								18	0.04	5.5	0.055	7
			400	750								20	0.04	6.1	0.061	7
			600	1110								23	0.05	7.0	0.070	7
Carbon steels																
Iron, carbon steel, 0.5% C	7.83	0.28	0	32	465	0.11	55	0.13	15.1	0.151	7					
			20	68								54	0.13	14.8	0.148	7
			100	212								52	0.12	14.3	0.143	7
			200	390								48	0.11	13.2	0.132	7
			400	750								42	0.10	11.5	0.115	7
AISI 1025	7.86	0.28	600	1110	486	0.12	51	0.12	13.4	0.134	5, 6					
			100	212								51	0.12	11.9	0.119	5, 6
			200	390								49	0.12	11.9	0.119	5, 6
			300	570								46	0.11	10.4	0.104	5, 6
			400	750								43	0.10	8.8	0.088	5, 6
			500	930								39	0.09	7.3	0.073	5, 6
			600	1110								36	0.09	5.9	0.059	5, 6
			700	1290								32	0.08	3.6	0.036	5, 6
			725	1337								30	0.07	2.7	0.027	5, 6
			775	1427								27	0.06	3.7	0.037	5, 6

Note: Some specific heat and conductivity values for AISI 1025 are estimated by two-point weighted averaging values from Ref 5.

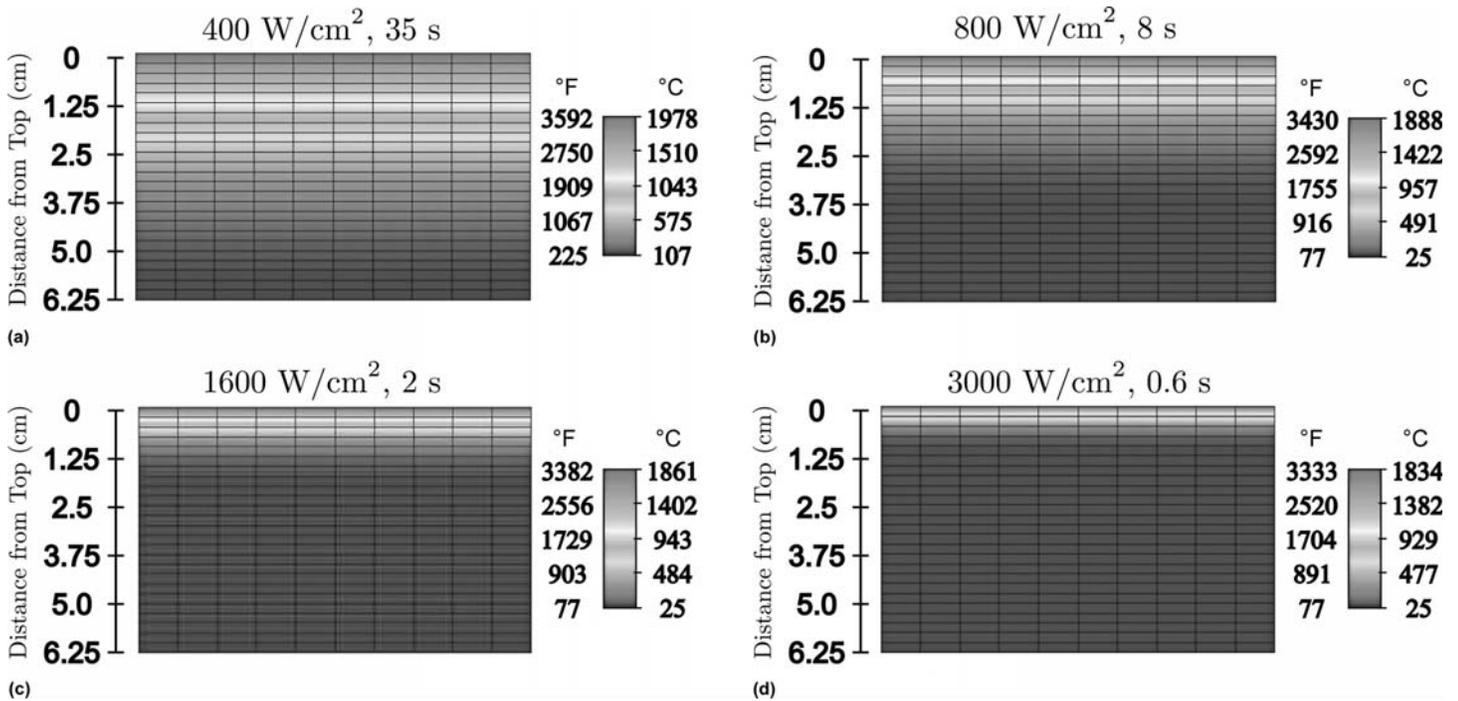


Fig. 4 Finite-element analysis temperature distribution results after a specific heating time in a thick steel plate heated uniformly on one surface as a function of applied heat intensity. Initial temperature of plate is 25 °C (77 °F), thermal conductivity is 50 W/m · K, specific heat capacity is 475 J/kg · K, density is 7800 kg/m³ (0.28 lb/in.³), and thermal diffusivity is 0.13 cm²/s.

with the dollar cost of the capital equipment. With reference to Fig. 3, 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. 6). 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 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 the inverse of the process interaction time, t_I (Fig. 5).

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. 7.

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. 8, with one slight modification. At levels above approximately 10^4 W/cm², 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/cm², 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, the width 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. 8 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

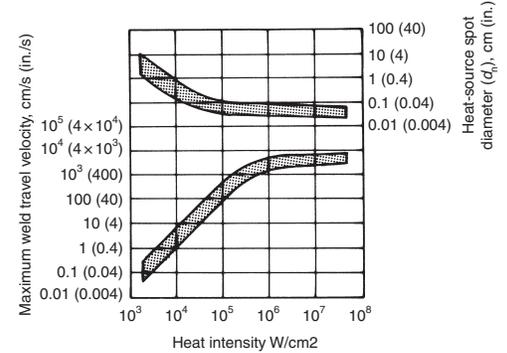


Fig. 6 Maximum weld travel velocity as a function of heat-source intensity based on typical heat-source spot diameters

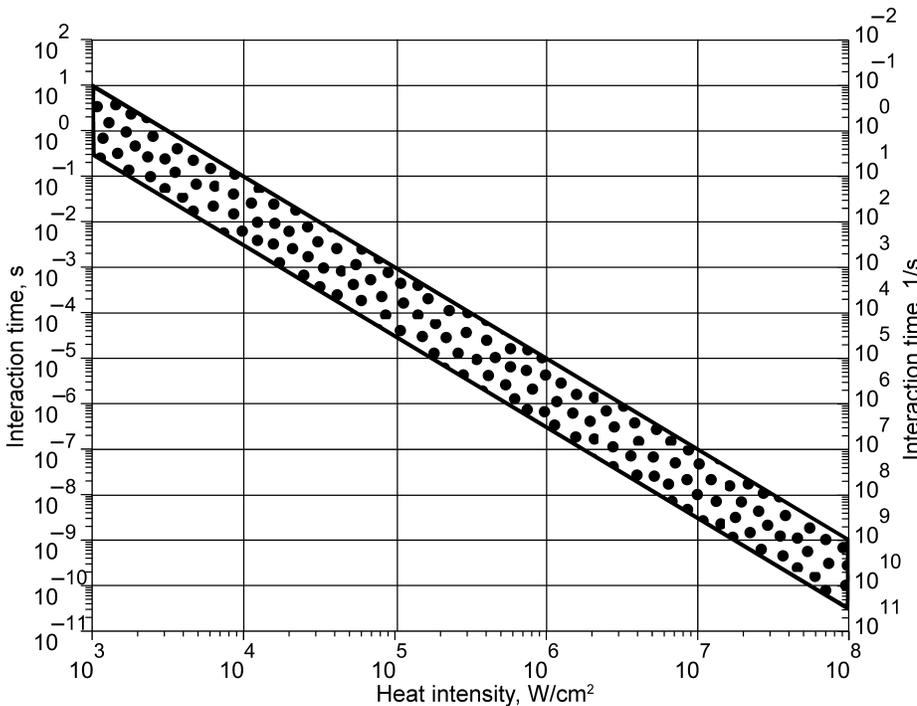


Fig. 5 Typical weld pool/heat source interaction times as a function of heat-source intensity. Materials with a high thermal diffusivity, such as copper or aluminum, would lie near the top of the band, whereas magnesium alloys and steels would lie in the middle. Titanium alloys, with very low thermal diffusivities, would lie near the bottom of the band.

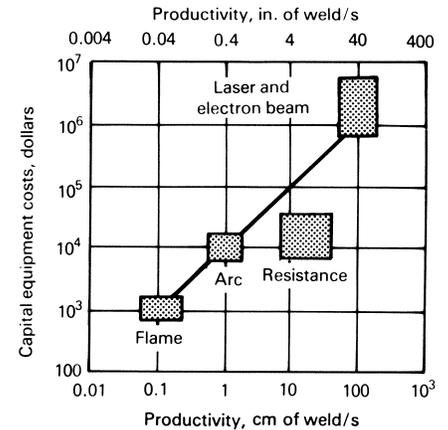


Fig. 7 Approximate relationship between capital cost of welding equipment and speed at which sheet metal joints can be produced

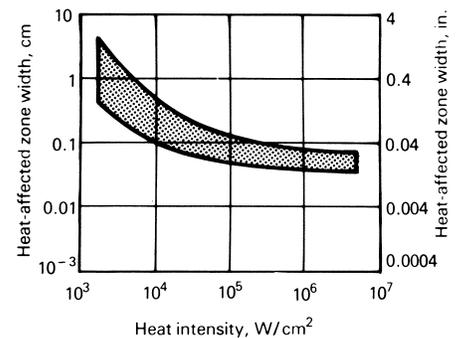


Fig. 8 Range of weld heat-affected zone widths as a function of heat-source intensity

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 for low-heat-intensity processes to more than 10 for 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 on fusion welding processes in this Volume.

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