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Welding in the World
The widely used resistance and fusion welding processes cannot overcome the incompatibility barrier inherent in metals, alloys, and nonmetals. The barrier has been cleared with vacuum diffusion bonding (Inventor’s Certificate No. 112460, USSR).

Diffusion bonding in vacuum does not require any expensive solders, electrodes, fluxes, or shielding gases. A weldment needs no subsequent machining as the process leaves no scale, slag, or flash; nor is there any associated loss of metal. A diffusion-bonded weldment does not gain in weight, as inevitably happens in fusion welding, brazing, or cementing. There is no warpage to guard against, and the properties of the materials in the joint area remain unaffected. The process is conducted at moderate temperatures and pressures, so the products are of a higher quality and have a longer service life.

Diffusion bonding is a process of high productivity, readily amenable to automatic control. It is capable, in a single operation, of joining hundreds or even thousands of workpieces produced by stamping, rolling or extrusion into complex shapes or structures, with the materials utilized to a high degree of completion. This has all made it possible to combine in diffusion bonding two distinct operations, fit-up and joining proper.

Joints made by diffusion bonding meet the requirements for most critical structures in terms of strength, toughness, tightness, and resistance to heat and corrosion. As the process is conducted under a vacuum, a diffusion-bonded joint has a minimum of impurity content, even in the case of highly reactive metals. As compared with shielding gases, vacuum does not involve any transportation and storage expenses.

Diffusion bonding can join over 730 pairs of dissimilar metals. In the USSR, over 960 vacuum diffusion bonding units are in operation. The economic return from their use has run into about a 100 million roubles in recent years.

Outside the Soviet Union, the process has been granted patents in Britain, Belgium, the GDR, the United States, France, the FRG, Sweden, and Japan.

Several organizations in the Soviet Union (the Fundamental Research Laboratory for Vacuum Diffusion Bonding and others) have been the first to develop advanced modifications of diffusion bonding applicable to solid inorganic materials, vacuum diffusion bonding machines using various sources of heat and pressing systems, and also automatically controlled units which have substantially expanded the field of application for the process.

This book is an attempt to pool the experience in vacuum diffusion bonding accumulated by a number of mechanical engineering works, research establishments, and colleges.

The Authors
An Outline of Diffusion Bonding in Vacuum

N. F. Kazakov

It is customary to class the existing welding processes into fusion welding and pressure welding. Accordingly, the definition adopted in the Soviet Union describes welding "as a process to make permanent joints by establishing interatomic bonds between workpieces through the action of local or general heating or plastic deformation, or both."

For interatomic bonds to be established, the workpieces must be brought together within the atomic spacing. Unfortunately, the surface geometry, chemical conditions, and physical state would usually stand in the way of bringing the pieces within the interatomic distance. Real surfaces are never ideally smooth or clean. Even carefully machined, a surface will show microscopic asperities with a height of hundreds or even thousands of molecular layers. So when two pieces are brought together, they will only come in contact at asperities. Also, the surface of any solid holds atoms from the surrounding medium, above all oxygen atoms, which form strong chemical bonds with the surface atoms. The simplest way to remove all of these obstacles is offered by fusion welding.

In fusion welding, the pieces to be joined are melted at their edges, the adsorbed substances vaporize or melt, and closure to within the interatomic distance takes place spontaneously as a weld pool is built up. A permanent joint forms as the weld pool cools and coalesces into a single body (along with the molten filler metal, if any has been used).

In pressure welding, the pieces to be joined are brought to within the atomic spacing through plastic deformation in the weld zone. Sometimes the mating surfaces are cleaned by, say, heating in vacuum or in a reducing atmosphere, autovacuum cleaning, etc. A full-strength joint is made owing to a physical contact, chemical bonds (which may be metallic, ionic, covalent, or their combination) between the atoms on the surfaces of the workpieces, and volumetric transformations.

The field of pressure welding can be divided into several subdivisions, such as resistance welding, gas-pressure welding, diffusion bonding, friction welding, ultrasonic bonding, stored-energy welding, explosion welding, etc.

Diffusion bonding, as its name implies, involves the interdiffusion of atoms across the interface of the weld in the solid and, sometimes, the liquid state (when a molten interlayer is used). The applied bonding pressure (or pressing load) causes the edges to move within the range of atomic forces. If there is a molten interlayer, the decisive factor is the pressing load which expels the interlayer from the joint. The pressing load is raised until all of the interlayer is squeezed out.
Diffusion bonding is carried out in suitably designed units fairly simple in their arrangement (Fig. 1-1). The pieces to be joined, 2, are loaded into a vacuum chamber, 1 (which is cooled by running water in the course of welding). A vacuum system, 3, maintains in the chamber sufficient rarefaction as a way of protecting the workpieces against intensive oxidation as they are heated for joining. Heat is supplied by the inductor, 4, of a high-frequency oscillator, 5. The pressing load applied to the workpieces is supplied by a hydraulic system, 6. When the joint is completed, the weldment is brought down to the specified temperature in the vacuum chamber.

The success or failure of the process is decided by three variables which need a constant watch and careful adjustment. These variables are the bonding temperature, the bonding pressure (or pressing load), and the holding time (duration of pressure).

The bonding temperature should be anywhere between 50% and 70% of the melting point of the most fusible metal in the composition. Elevated temperature aids the interdiffusion of atoms across the interface of the weld, and this assists surface deformation (the crushing of surface asperities).

The bonding pressure or pressing load should ensure a tight contact between the edges of the pieces. It must be sufficient to aid deformation of surface asperities and to fill all the voids in the weld zone. If the pressure is not sufficient, some of the voids will be left unfilled, and the strength of the joint will be impaired. Important ly, the pressing load disperses oxide films — this leaves a clean surface, and aids the diffusion and coalescence.

The holding time (duration of pressure), at a specified bonding temperature and a specified bonding pressure, must, in most cases, be kept to a minimum from

![Fig. 1-1 Basic features of a vacuum diffusion bonding unit](image-url)
AN OUTLINE OF DIFFUSION BONDING IN VACUUM

physical and economic considerations. It should be just sufficient for an intimate contact to be formed and for diffusion processes to take place. An excessive diffusion time might leave voids in the weld zone or even change the chemical composition of the metal or lead to the formation of brittle intermetallic phases (when dissimilar metals or alloys are being joined).

The vacuum in the welding chamber is usually maintained at $10^{-1}$-$10^{-3}$ Pa. Sometimes, the medium in the chamber may be an inert gas (dry argon or dry helium with a dew point of below 216 K), hydrogen, or various gas mixtures.

For the joint to be sound, there must be a good surface contact, the edges must be smooth and fit to each other snugly. Soft metals, such as aluminium, magnesium, tin, and gold, need to be surface-finished prior to diffusion bonding so that the surface asperities are not more than 40 to 80 $\mu$m high. Hard alloys, refractory metals, high-temperature alloys, tool steels, and nonmetal materials call for a more thorough surface finish. Surface asperities (roughness) in such cases should be not more than 2.5 $\mu$m high or even lower. The use of an interlayer of a readily deformable material is desirable.

To repeat, diffusion bonding is a process by which a joint can be made between similar and dissimilar metals, alloys, and nonmetals, through the action of diffusion of atoms across the interface, brought about by the bonding pressure and heat applied for a specified length of time.

Sometimes, diffusion bonding is referred to as pressure joining, autovacuum welding, thermo-compression welding, solid-state or solid-phase welding, etc. This may introduce an element of confusion into the understanding of the essence and mechanism of diffusion bonding. To avoid all this, a relevant USSR State Standard defines both the process and the associated terms. As far back as 1962, N. F. Kazakov, who is credited with the invention of diffusion bonding, described diffusion bonding in the following terms: “In this case, a monolithic joint is due to the formation of metallic bonds as a result of local plastic deformation at elevated temperature, closest approach of the surfaces, and interdiffusion in the surface layers of the metals brought in contact.” More recently diffusion bonding has been used to join both metals and nonmetals to metals and nonmetals, so in addition to metallic bonds other types can appear in the weld zone. Accordingly, the International Welding Institute has adopted a modified definition proposed by Kazakov: “Diffusion bonding of materials in solid state is a process for making a monolithic joint through the formation of bonds at atomic level, as a result of closure of the mating surfaces due to local plastic deformation at elevated temperature which aids interdiffusion at the surface layers of the materials being joined.”

Since the principal factor responsible for the formation of the joint is diffusion, it appears that the term “diffusion bonding” or “diffusion welding” is most relevant. It includes the two key words, diffusion and bonding, that is, the processes by which pieces are joined into a single whole. The bonding variables (temperature, load and time) vary according to the kind of materials to be joined, surface finish, and the expected service conditions.

Diffusion bonding offers a number of advantages over fusion welding and brazing. This is clearly seen from their comparison in Table 1-1.
<table>
<thead>
<tr>
<th>Particulars</th>
<th>Fusion welding</th>
<th>Diffusion bonding</th>
<th>Brazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contacting method</td>
<td>Autogenous fusion, autogenous fusion and pressure</td>
<td>Pressure (no fusion)</td>
<td>Contact fusion, contact fusion and pressure</td>
</tr>
<tr>
<td>Bonding</td>
<td>Cohesive</td>
<td>Adhesive, diffusion</td>
<td>Cohesive, adhesive</td>
</tr>
<tr>
<td>Heating</td>
<td>Local</td>
<td>Local, total</td>
<td>Local, total</td>
</tr>
<tr>
<td>Temperature</td>
<td>Melting point of parent metal</td>
<td>0.5-0.7 of melting point of parent metal</td>
<td>Somewhat above melting point of solder</td>
</tr>
<tr>
<td>Surface preparation</td>
<td>Less exacting</td>
<td>Careful</td>
<td>Less exacting</td>
</tr>
<tr>
<td>Fit-up</td>
<td>Lenient</td>
<td>Precise</td>
<td>With capillary gap</td>
</tr>
<tr>
<td>Materials</td>
<td>Metals, alloys</td>
<td>Metals, alloys, nonmetals</td>
<td>Metals, alloys, nonmetals</td>
</tr>
<tr>
<td>Joint formation</td>
<td>Gradual</td>
<td>Simultaneous</td>
<td>Simultaneous, gradual</td>
</tr>
<tr>
<td>Edge preparation</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Joining of dissimilar materials</td>
<td>Limited</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Stepwise conduct of process</td>
<td>Limited</td>
<td>Unlimited</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Susceptibility to solidification</td>
<td>Strong</td>
<td>None</td>
<td>Weak</td>
</tr>
<tr>
<td>cracking</td>
<td></td>
<td></td>
<td>Blowholes, shrinkage, diffusion</td>
</tr>
<tr>
<td>Porosity</td>
<td>Shrinkage, blowholes</td>
<td>None</td>
<td>Limited</td>
</tr>
<tr>
<td>Overlapping with heat treatment</td>
<td>No</td>
<td>Unlimited</td>
<td>Limited</td>
</tr>
<tr>
<td>Warpage</td>
<td>Heavy</td>
<td>None</td>
<td>Light</td>
</tr>
<tr>
<td>Principal types of joint</td>
<td>Butt, lap</td>
<td>Flat (butt, lap, tapered plug in socket, between</td>
<td>Butt, lap</td>
</tr>
<tr>
<td></td>
<td></td>
<td>cylinders, spherical, curvilinear)</td>
<td></td>
</tr>
<tr>
<td>Joining in hard-to-reach places</td>
<td>Limited</td>
<td>Unlimited</td>
<td>Limited</td>
</tr>
<tr>
<td>Product precision</td>
<td>Low</td>
<td>Fairly high</td>
<td>High</td>
</tr>
<tr>
<td>Disassembly of joint</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Vibration survival</td>
<td>Low</td>
<td>Very high</td>
<td>High</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>Satisfactory</td>
<td>Fairly high</td>
<td>Low</td>
</tr>
<tr>
<td>Strength</td>
<td>Close to that of parent metal</td>
<td>That of parent metal</td>
<td>That of solder</td>
</tr>
<tr>
<td>Air pollution and radiation emission</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
A very important distinction of diffusion bonding is the high quality of joints. It is the only process known to preserve the properties inherent in monolithic materials, in both metal-to-metal and nonmetal joints. With properly selected process variables (temperature, pressing load, and time), the material at and adjacent to the joint will have the same strength and plasticity as the bulk of the parent material(s). When the process is conducted in vacuum, the mating surfaces are not only protected against further contamination, such as oxidation, but are cleaned, because the oxides present dissociate, sublime, or dissolve and diffuse into the bulk of the material. This is why a diffusion weld is free from incomplete bonding, oxide inclusions, cold and hot cracks, voids, warpage, loss of alloying elements, etc. Since the edges are brought in intimate contact, there is no need for fluxes, electrodes, solders, filler materials, etc. Diffusion-bonded parts usually retain the original values of ultimate tensile strength, angle of bend, impact toughness, vacuum tightness, etc. In terms of strength, ductility, tightness, and corrosion resistance, diffusion-bonded joints meet the requirements for the most critical applications. Diffusion bonding has extended the service life, quality and reliability by a factor of 10 to 12 for a wide range of products, and has made it possible to develop fundamentally new structures, to simplify techniques and procedures, and to replace scarce or expensive materials. A major distinction of diffusion bonding, the high stability of mechanical characteristics, enables one to limit quality control to a random check in which just a few parts are examined for quality and compliance with specifications instead of a large sample or the entire lot. This is especially valuable because simple, inexpensive and reliable techniques of nondestructive testing which could be used in a welding or an assembly shop are nonexistent in some cases.

Diffusion bonding can turn out weldments extremely intricate in shape, but with joints having the same properties as the parent materials. With it, one can make shapes that could not be fabricated earlier or which would be too expensive to make by conventional processes. Dimensional tolerances for diffusion-bonded products are the same or even more stringent than those for machined parts. Since diffusion bonding makes unnecessary most of the fasteners, there is less tendency towards stress-induced corrosion which is a crucial matter for products with a long service life. The materials to be joined may vary in thickness from a few micrometres (foil) to several metres.

In recent years, a theory of diffusion bonding has been developed and important results obtained on the diffusion processes involved in the formation of a monolithic bond between solid inorganic materials of any kind without affecting their physical and mechanical properties. Now diffusion bonding can be used to join not only similar, but also dissimilar metals and alloys widely differing in thermo-physical characteristics; the process can be used to weld heavy thicknesses and any complicated shapes from porous, fibre and powdered materials; to join nonmetals (such as glass, semiconductors, ceramics, pyrosils, quartz, graphite, ferrites, cermets, and the like) to metals; and to repair or reclaim worn or broken components for various machinery.

Now diffusion bonding has a companion — diffusion metallurgy which is gaining application on an ever wider scale. A process has been developed for thermal
vacuum treatment which extends the service life and reliability of machines and tools. Research has led to a variety of multicomponent composites which combine the properties of metals, alloys, and nonmetals.

By its nature, diffusion bonding lends itself readily to automation. Automated diffusion bonding can join in a single pass tens or even hundreds of components, fabricated by stamping, rolling, casting, or extrusion, into complex assemblies and structures with a high utilization of materials.

The basic variables of diffusion bonding (temperature, pressing load, vacuum, and holding time) can readily be programmed. As a rule, equipment for diffusion bonding is either semiautomatic with a minimum of manual labour, or automatic, operating with practically no human intervention. The high degree of mechanization of diffusion bonding equipment, the high quality and the longer life of products and the high sanitary standards of the environments make diffusion bonding a far more attractive process than any other conventional welding processes.

A further advantage of diffusion bonding is that it can join any components, however complicated their shape or cross section may be. Among other things, it can butt-join pipes and bars, to butt- and lap-weld flat pieces, and to make a variety of joints — corner, plug lap, coach, tapered, spherical, involute, etc. The configuration of the workpiece having a flat surface, and its dimensions do not affect the quality of the diffusion bond; they can only control the choice of the heat source and pressing arrangement to transfer the bonding pressure to the workpiece.

Until quite recently, diffusion bonding was applicable to a limited range of shapes and cross-sectional areas at the point of contact. Also, the space within the vacuum chamber was not utilized fully. To circumvent the limitations, new diffusion bonding units have been developed, such as multichamber (the rotary type), continuous (the airlock type), and hopper-loaded. There are also units operating to a preprogrammed sequence, with vacuum chambers set up directly on the workpiece, etc. These chambers can accommodate workpieces up to 750 kN in weight, up to 50 m in length, and 58.8 mm in diameter, and the blanks are fed in on air cushions.

Diffusion bonding has been used to fabricate silver- or copper-clad chemical units 3 m high and 1.86 m in diameter, wear-resistant dies to punch stampings for the magnetic cores of electric motors, cutting and measuring tools, metal-ceramic pressure-seal feed-throughs, ferrite and cermet assemblies, the elastic elements of transducers, sandwich panels, fluidics modules, radial-turbine wheels, turbine blades, porous tubes for the chemical and gas industries, valves, pistons and cylinder liners for internal-combustion engines, and many other products. In the electronics industry diffusion bonding is used to make and assemble slow-wave structures for some electron tubes, to join nickel foil 3 μm thick to a substantial component, and aluminium foil 8 μm thick to a copper grid. Diffusion bonds are vacuum-tight, heat-resistant, and vibration-proof, with the diffusion-bonded products retaining their high accuracy, dimensions, and shape.

Diffusion bonding is a highly economical process. It does not involve any expensive solders, special grades of wire or electrodes, fluxes, and shielding gases. Moreover, there is no need for the subsequent machining, so there is no associated loss of valuable metal. A diffusion-bonded product does not gain in weight as hap-
pens with ordinarily welded, brazed, or glued components. The properties of the metal in the weld zone remain as they were, so postheat treatment is not mandatory. Pieces of diffusion bonding equipment can be built into machining or assembly flow lines, so no facilities are necessary to transfer components between machining and welding shops. The power demand for diffusion bonding is one-fourth to one-sixth of what is taken up by, say, resistance welding.

Further advantages of diffusion bonding are high sanitary standards of the working environments and freedom from ultraviolet radiation, harmful gas emission, metal spatter, and finely divided dust.

Diffusion bonding has contributed to advances in other fields. As Academician G. N. Flerov believes, the discovery of the 106th element in the Periodic Table has been expedited by the Vacuum Diffusion Bonding Fundamental Research Laboratory which was asked to devise ways and means for reliably joining the working substance to the electrode of a source operating in the plasma discharge. An important project has been carried out for Academician A. M. Prokhorov, a Nobel Prize winner, in connection with his work on powerful gas lasers.

A major limitation of the process is that a good deal of time has to be spent on pumping out the vacuum chamber, cleaning and fitting up the pieces to be joined. Currently, work is under way to avoid this, and it may be expected that an answer will be found before long.

The success or failure in using diffusion bonding commercially depends on the scale of production and the quality of the equipment used.

Recently, a change of attitude has taken place as regards diffusion bonding. From a process applicable to materials which can be joined by conventional welding or brazing with difficulty, if at all, it has grown to a process readily available to join both small and large workpieces. Today, it is highly competitive with existing fusion welding and brazing processes.

Diffusion bonding is a promising process which is bound to gain more and more in importance as the use of alloyed steels, special alloys, nonmetallic and composite materials is increased. In the author's opinion, its further advance will take a two-pronged road. One will be concerned with further perfection of its techniques and procedures, methods of heating, transfer of pressing load, mechanization and automation, nondestructive testing, and mechanized and automated equipment. The other will be related to getting a better insight into the mechanism of diffusion bonding and bringing out the yet-untapped potentialities of the process in its application to large and critical components for instruments, apparatus, and machines.

Bibliography

A Theory of Diffusion Bonding

N. F. Kazakov

2.1 The Mechanism of Bond Formation in Pressure Welding

Although a multitude of welding processes are currently used on a commercial scale, it is pressure welding that is leading the field.

Pressure welding refers to a process in which a joint is made at temperatures below the melting point of the metals being joined, without any solder used, and under a pressing load sufficient to bring about the necessary plastic deformation of the pieces.

Several hypotheses have been advanced to explain how a bond is formed in solid state. One is the film hypothesis due to S. B. Ainbinder et al. By this hypothesis, all metals and alloys possess an equal property to seize when clean surfaces are brought together within the range of interatomic forces. The observed differences in weldability among various metals are explained by the presence of surface films. The oxide films which prevent joining can be hard, brittle, viscous, or plastic. When the metals being joined are subjected to cold plastic deformation, the hard and brittle films are broken up to expose clean metal layers which, on being brought together within the range of interatomic forces, form a strong bond. If at least one of the two metals has a plastic oxide film on its surface, plastic deformation will cause the oxide film to spread along with the underlying layers, and no bond will be formed. In some patterns of deformation, however, oxide films play a minor role.

The recrystallization hypothesis puts emphasis on recrystallization as the principal factor in bond formation. By this hypothesis, deformation and the accompanying strain hardening, coupled with exposure to relatively high temperatures at the interface, cause the atoms in the lattices of the materials being joined to move to other sites so that there appear, at their boundaries, grains common to both pieces with the result that a bond is formed. The proponents of the hypothesis have not been able, however, to present any convincing proof. Among other things, a diffusion bond can be formed at a temperature as low as 123 K; the weld zone displays high hardness; the rate of deformation does not affect the strength of the resultant bond obtained by cold welding; X-ray diffractometry reveals no recrystallization in cold-bonded aluminium; and a strong bond is produced with the formation of metallides (compounds of metals with metals and other elements — oxides, hydrides, nitrides, carbides, etc.) at the interface.

According to the energy hypothesis, for a diffusion bond to form the atoms of the metals being joined should be raised to what may be called the energy threshold of seizure or adhesion. At this threshold, the orientation of atomic bonds is no longer a factor, metallic bonds come into being between the atoms at the surfaces, and the
interface between the two pieces disappears. The combined plastic deformation necessary for the onset of seizure decreases in proportion to the increase in the energy of the atoms in the metals. For example, heating or elastic deformation, which raise the energy of the atoms, can bring the metal closer to the condition necessary for seizure to take place. In the opinion of A. P. Semenov, the seizure of metals is a nondiffusion process. At elevated temperatures, however, a diffusion process is superimposed on the nondiffusion seizure within the contact zone. The energy hypothesis fails to explain which properties of the metals being joined are responsible for the degree of seizure.

By the dislocation hypothesis, due to J. Friedel, E. I. Astrov, and some others, the joint plastic deformation causes dislocations to move to the surface. In doing so, they break up the oxide films present and produce steps each an interatomic distance high. One body of opinion is that the emergence of dislocations at the contact surface reduces resistance to plastic deformation and aids in joining the metals. Another believes that the emergence of dislocations increases the number of high and low spots on the surface, and this promotes a greater plastic deformation at the contact surfaces than within the bulk of the metals. Thus, seizure, or bond formation, is an outcome of the plastic flow of the metal within the contact zone. The proponents of the dislocation theory argue that seizure may also be accompanied by diffusion processes, but there is no consensus on the mechanism of seizure.

The electron hypothesis has been advanced by G. V. Samsonov et al. In their opinion, the surface seizure results in the formation of stable electron configurations involving the atoms of the metals in contact. If the electron configurations in the two metals being joined have high statistical weights, their adhesion is considerably weakened [13]. It has been demonstrated that knowledge of the electron configurations of metals and elemental atoms in chemical compounds gives an insight into their weldability, wettability, diffusion processes, etc.

In accord with the diffusion hypothesis [7-11], the formation of a sound bond between the surfaces in contact depends on the interdiffusion of atoms into the bulk of the specimens. The surface atoms of a metal have free, unfilled bonds (vacancies) which capture any atom moving within the range of interatomic forces. A free atom has an excess energy as compared with the atoms in a condensed system, and its attachment is accompanied by release of energy. This spontaneous union can be observed within volumes of a homogeneous liquid. The picture is different in solids. Now a substantial amount of additional energy has to be put in, and elaborate techniques have to be used in order to bring the atoms to be joined closer together.

There are many more hypotheses advanced to date; we have only dwelt on the most plausible and commonly accepted.

Despite the seeming simplicity of the process, pressure welding involves a sequence of stages or steps: the surfaces to be joined are first brought in contact; the surface oxide and adsorbed films are then broken up; the surface layers are activated as a result of deformation; volumetric diffusion processes take place, recrystallization follows, etc. These stages, undoubtedly overlapping in actual practice, testify to the complexity of pressure welding, because of which the mechanism
2.1 BOND FORMATION IN PRESSURE WELDING

of the process cannot, at times, be explained from a single point of view. Lack of experimental data about the effect of the various factors and parameters on bond formation in pressure welding also contributes to the existing disagreement on the nature and mechanism of bonding. Yet, a general idea has of late taken shape. Most investigators agree that pressure welds are produced as a result of the metallic bonds that form between the metals being joined. Ya. I. Frenkel views any metal specimen as a collection of positively charged ions located, ideally, at the lattice sites, and a large number of free electrons interacting with many ions in that specimen at a time. This interaction of the electron cloud with ions is responsible for the existence of the specimen as a single body. Given certain conditions, a similar interaction may take place between the surfaces of two metal specimens being joined. When they are brought together to within the range of interatomic forces, the interaction causes the atoms to form a bond which is as strong as it is within the bulk of the metal. In other words, the atoms of a metal specimen tend to unite with similar or any other atoms and molecules. In doing so, they may form complexes, however large, or volumes of metal.

If two specimens brought in contact had ideally smooth, clean and parallel surfaces, metallic bonds sufficient for a joint to form and to have the same strength as the parent metal would be established spontaneously, and no external energy input would be necessary. Ideal surfaces are nonexistent, however. The surfaces of real metal specimens are always covered by films of oxides and adsorbed grease and gases, which interfere with the formation of metallic bonds, and are never smooth. Any specimen, no matter how carefully it has been machined, shows a wavy and rough surface with a multitude of microscopic asperities. So the pieces being joined first touch each other at the ridges of these high spots, and the contact is of necessity a discontinuous one. In the unloaded state, the contact area at each asperity varies with surface quality and some other factors and ranges between a fraction of a square micrometre and thousands of square micrometres. Although the number of contacting asperities at any given instant may be large, the total actual area of contact, $\Sigma A_{act}$, is only a small fraction of the nominal area of contact, $A_n$, being from 0.01 $A_n$ to 0.000 01 $A_n$. Obviously, with the total area of contact of such a size the resultant joint can have a strength substantially lower than that of the parent metal, and then only if the interaction due to metallic bonds between the mating surfaces takes place at all, that is, only if there appear initial sites of seizure (adhesion) and their local strength is sufficiently high. In fact, even with a large number of seizure sites, no welded joint may have formed yet. So, seizure (adhesion) and welding are not the same because they occur on different scales. A single seizure site may be treated as the initiation of a welded joint, and for the latter to form it must spread over all or the greater part of the nominal contact area. For two metal specimens, $A$ and $B$ to be joined, they must be brought together to within a distance sufficient for a strong bond between their atoms to form. The energy of interaction between the atoms will then be a minimum

$$E = U - TS$$

(2-1)

where $E$ is the free energy for constant volume, $v$, $U$ is the internal energy of the system, $T$ is the temperature of the joint, and $S$ is the entropy.
When brought to within such a distance, \( r \), the atoms form a most stable system, because any increase or decrease in interatomic distance would increase the energy of atomic interaction (Fig. 2-1). The above scheme can only occur in exceptional cases, such as when two metal specimens with juvenile surfaces are brought together under an ultra-high vacuum (1.33 \( \times \) 10\(^{-6} \) Pa).

Actually, the situation is far more complex. As already noted, a real specimen, no matter how well it is machined, presents a microscopically rough surface. In the best of surface finishes, the asperities are 0.3 to 1 \( \mu \)m high. When two metal surfaces are brought together, the interatomic forces of attraction begin to be felt at distances anywhere between 10\(^{-4} \) and 5 \( \times \) 10\(^{-4} \) \( \mu \)m. Therefore, if the pressing load is small and does not bring about marked plastic deformation, atomic interaction will be solely observed at individual asperities. In the clearances, only adhesion bonds between the metal and the gas or liquid molecules adsorbed on the metal surface will exist. For seizure to spread over a larger area and, as a consequence, for the actual welding to take place, it is necessary to apply either a high pressure which would bring about plastic deformation in the metal around the contact area, or a strong heat which would enhance the activity and mobility of the species in the crystal lattice. When both pressure and heat are applied together, they produce in the weld zone a concentration of energy which, in Academician P. A. Rebinder’s words, is sufficient to bring about a rearrangement of the surface layers in the mating specimens, and also to give rise to the slower secondary processes, such as interdiffusion, recrystallization and so on. The latter can proceed either spontaneously or need far less energy than is necessary to form areas of direct contact between the specimens.

If, now, hot pressure welding is conducted in a vacuum, this will not only protect the metal surfaces against further contamination (such as oxidation), but also clean them through the desorption, sublimation, or diffusion of the oxide coating into the bulk of the material. This can produce a metallic bond at the contact surfaces, but this bond is sometimes not sufficiently strong to assure a good weld. A far better weld is made when the weld zone is extended into the bulk of the material. This extension occurs through interdiffusion which is a form of mass transfer.

The effect of diffusion processes on recrystallization and the formation of an intermediate zone varies with the welding temperature. If the two pieces being joined widely differ in physical and chemical properties, this zone may display changes in chemical bonds and composition. Within it, the type and parameters of the lattice and some physical properties of the parent metals may change gradually (from the

![Fig. 2-1 Potential energy as a function of atomic spacing](image-url)
2.2 DIFFUSION PROCESSES IN MATERIALS

properties associated with one piece to those of the other). In other words, pressure welding can produce a monolithic joint only if bonds are formed at the atomic level as the pieces to be joined are brought together and subjected to plastic deformation. The joint thus made gains in strength and reliability as interdiffusion promoted by heating causes the weld zone to expand.

2.2 The Basic Pattern of Diffusion Processes in Materials

Diffusion refers to the actual transport of mass in the form of discrete atoms through the lattice of a crystalline solid. Diffusion processes are fundamental in a large class of effects in metals and alloys (grain growth, polymorphism, relaxation, recrystallization, homogenizing heat treatment, precipitation hardening, surface impregnation, sintering, pressure welding, etc.) [3, 4, 5, 7-10].

As the present-day views hold, metals and alloys, when solid, are each a system of positive ions regularly distributed in space, and relatively free electrons which move within well-defined energy bands. The ions oscillate at a very high frequency (about $10^{13}$ Hz), and it is thermodynamically feasible for them to move to another, energetically more attractive site. This motion is greatly enhanced by a rise in temperature.

The diffusion (both self- and heterodiffusion) of atoms can take place only if the diffusing atoms have a sufficient store of energy for their migration through the lattice. At any temperature, the mean energy of oscillation of atoms in the lattice is a fixed quantity. This energy, however, varies from atom to atom in accord with laws of probability. Each atom in a state of continuous thermal vibration may collide with adjacent atoms. Through collisions, atoms pick up abnormally high velocities each corresponding to a particular local limit of temperature. In this way, the distribution of thermal energy within the lattice is subject to fluctuations. The distribution of atoms in the lattice by energy is shown in Fig. 2-2. The initial portion of the curve corresponds to the higher energy, $E_1$, displayed by a minority of atoms at temperature $T_1$, as compared with the mean energy, $E_2$, of the majority of atoms.

![Fig. 2-2 Energy distribution of atoms in a metallic lattice](image)

![Fig. 2-3 Energy of activation for the diffusion of atoms: $x_1$, $x_3$, equilibrium positions (lattice sites); $x_2$, middle position](image)
When the temperature of the specimen is raised to $T_2$, the mean energy of the majority of atoms, $E_2$, goes up to $E_3$, and that of the minority to $E_4$. Locally, the temperature within the lattice may be so high that the crystal may even vaporize. Then an atom may free itself from the action of the forces around it — now it will be free to move about. If an atom moving at a high velocity comes near an open surface, it may escape into the surroundings (sublimation). As is seen, for an atom to be able to move through the lattice, it must be activated. The activation energy for the diffusion of atoms depends on the magnitude of the energy barrier, $Q$ (Fig. 2-3) which is in turn determined by the strength of bond between atoms. Diffusion proceeds gradually; the elementary displacement, $x_i$, of an atom in the lattice is a few angstroms. From state to state, atoms move in jumps.

Diffusion might proceed by four mechanisms.

1. Exchange of places between two adjacent atoms (Fig. 2-4a). This would involve the expenditure of a large amount of energy because each atom must move a distance of two atomic diameters, and the ensuing local distortion of the lattice would be appreciable. Therefore this mechanism should be ruled out.

2. Motion of interstitial atoms (Fig. 2-4b). The atom at lattice site 1 moves to an interstice 2. Its further motion will be through the interstices 3, 4, 5, and 6. For this to happen, an appreciable amount of energy must be imparted to the atom. Therefore, this mechanism can exist in the case of heterodiffusion in solid solutions where an interstitial atom is far smaller than an atom of the parent metal.

3. Circular exchange of four atoms (Fig. 2-4d). Now four atoms at a time move around a ring. This mechanism is most of all likely to exist in metals with a closely packed lattice.

4. Motion of vacancies (Fig. 2-4c). Now vacancies in the lattice change places with adjacent atoms. The motion of vacancies is in a direction opposite to that of atoms. On taking up the vacancy at 1, atom 2 clears room for atom 3, and atom 4 can now move into the site previously occupied by atom 3, leaving behind a vacancy.

Fig. 2-4 Mechanisms by which atoms move in a metallic lattice
2.2 DIFFUSION PROCESSES IN MATERIALS

As has been found theoretically, the activation energy for self-diffusion in copper should be 1 008 kJ mol\(^{-1}\) for the exchange mechanism, 966 kJ mol\(^{-1}\) for the interstitial mechanism, 269 kJ mol\(^{-1}\) for the vacancy mechanism, and 378 kJ mol\(^{-1}\) for the ring mechanism. The experimental figure is 210 kJ mol\(^{-1}\). Hence, of the four likely diffusion mechanisms, pure metals and alloys with a substitutional solid-solution structure show preference for the vacancy mechanism. With it, an atom at a lattice site may jump to an adjacent site. For this to happen, the diffusing atom should be activated thermally so that it can clear the potential barrier between the sites, equal to \(Q_v\), the activation energy for vacancy jump. The probability of a jump is a function of the equilibrium concentration of vacancies, \(C_v\), in the metal such that

\[
C_v = C \exp(-Q_v/RT)
\]  

(2-2)

where \(Q_v\) is the activation energy for vacancy formation, \(C\) is a constant, \(R = 8.315\) kJ mol\(^{-1}\) is the gas constant, and \(T\) is the temperature in kelvins.

The activation energy for diffusion is usually taken as the sum of the activation energy for vacancy formation, \(Q_v\), and the activation energy for vacancy jump, \(Q_j\).

So far we have only considered vacancies. Solids are, however, abundant in other lattice imperfections, called dislocations. The rate of diffusion through the dislocation core is a function of Burgers' vector and may be very high. Grain boundaries, too, may be treated as lattice imperfections. The observed activation energy for diffusion along grain boundaries is about half the figure for diffusion by the bulk mechanism. The surface migration of metallic atoms shows a low activation energy as well. By Fick's first law, the rate of diffusion is defined as the quantity of material, \(q\), diffusing across an interface plane of unit area, \(dA\), in unit time, \(dt\), through a distance, \(dx\). The quantity of diffusing material, \(q\), is a function of the concentration gradient of the element involved, \(dc/dx\), in a direction normal to the interface (Fig. 2-5) and is proportional to the diffusion coefficient, \(D\), or mathematically

\[
q = -D \frac{dc}{dx}
\]  

(2-3)

The "−" sign on the right-hand side of the equation indicates that the diffusion proceeds from a region where the concentration of the element is high towards a region where its concentration is low. Numerically, the diffusion coefficient is the weight of material diffusing across unit area in unit time under unit concentration gradient \((dc/dx = 1)\).

Variation in concentration with time is defined by Fick's second law

\[
\frac{dc}{dt} = D(\frac{d^2c}{dx^2})
\]  

(2-4)

\[
C
\]

\[
dx
\]

FIG. 2-5 Flow of atoms across an element of section
It is assumed that the diffusion coefficient is independent of concentration. As the temperature is raised, the rate of diffusion increases exponentially

\[ D = D_0 \exp(-\frac{Q}{RT}) \] (2-5)

where \( D_0 \) is the frequency factor depending on the type of lattice and the oscillation frequency of the diffusing atom, \( Q \) is the activation energy for (or heat of) loosening in kJ mol\(^{-1}\), \( R = 8.315 \) kJ mol\(^{-1}\) is the gas constant, and \( T \) is the temperature in kelvins. The quantity \( Q \) characterizes the binding energy of atoms in the lattice. The larger its value, the greater the energy required to loosen the lattice or, which is the same, the higher the energy required for an atom to jump from a site to another site or an interstice. The activation energy is a maximum in the case of bulk diffusion, \( Q_b \), and is smaller than the activation energy for boundary diffusion, \( Q_{\text{bound}} \), and the activation energy for surface diffusion, \( Q_s \), that is

\[ Q_b > Q_{\text{bound}} > Q_s \]

Diffusion proceeds predominantly over the surface or along the boundaries of grains and mosaic blocks because the lattice distortion and lattice imperfections (vacancies, dislocations, stresses, and cracks) are most pronounced there. The rate of diffusion along grain boundaries depends on the angle between the grain axis and the direction of diffusion. From the viewpoint of diffusion bonding, it is attractive to speed up diffusion by producing an excess concentration of vacancies through plastic deformation. In specimens of silver subjected to twisting, the rate of diffusion has been found to increase at least hundredfold. This increase is proportional to the rate of deformation, that is, the instantaneous concentration of vacancies. Excess vacancy concentration can also be produced by rapid cooling (quenching) or irradiation with highly energetic particles.

2.3 The Processes and Factors Responsible for Joint Formation in Diffusion Bonding

Several physico-mechanical processes usually take place in diffusion bonding at the same time. These are diffusion, recrystallization, creep, formation and motion of dislocations, formation and motion of vacancies and interstitials. Each can, to a varying degree of accuracy, be evaluated by the following well-known equations

\[ A_1 = B_1 \exp(-\frac{Q_1}{E_0}) \] (2-6)

\[ A_2 = B_2 + C_2 \exp(-\frac{Q_2}{E_0}) \] (2-7)

\[ A_i = B_i + C_i \exp(-\frac{Q_i}{E_0}) \]

Here, \( Q_i \) is the activation energy for the respective process, and \( E_0 \) is the thermal energy imparted to the test specimen. Their ratio appears as an exponent in all equations and is a dimensionless quantity which may serve as a similarity criterion for the processes involved.

Thus, with regard to diffusion bonding, it is not enough to limit consideration only to the thermal quantities associated with a particular physico-mechanical pro-
cess. Account must always be taken of two factors, mechanical energy and thermal energy, because the two always come into the picture at the same time.

Let $M$ be the factor related to the mechanical energy expended to deform a volume $V$. Then in terms of the ratio of bonding pressure, $p$, to the yield strength, $\sigma_y$, it can be defined as

$$pV/\sigma_yV = M$$

Similarly, let $N$ be the factor related to the thermal energy imparted to the same volume. Then, in terms of the ratio of the instantaneous temperature, $T$, to the melting point, $T_m$, it can be defined as

$$T\gamma cV/T_m\gamma cV = N$$

where $\gamma$ is the density of the metal, and $c$ is its specific heat.

Suppose that the two factors may be added together. Then Eqs. (2-7) and (2-8) can be re-arranged to yield the equation of a line in straight segments

$$\frac{p}{(M + N)\sigma_y} + \frac{T}{(M + N)T_m} = 1$$

The above form of relation between the bonding pressure, $p$, and the bonding temperature, $T$ (the dashed line in Fig. 2-6) does not actually occur in diffusion bonding. The actual relation is $p = f(T)$; it is the same for all pressure welding processes (the solid line). The relation holds when joints made at various temperatures and pressures and also with different methods of heating and different holding times (durations of pressure) and temperatures have about the same strength. The relation

![Fig. 2-6 A plot of pressing load versus bonding temperature in pressure welding](image1)

![Fig. 2-7 Variations in the potential energy of interaction between metallic crystals in diffusion bonding](image2)

$E_E$, energy of electrostatic (van der Waals) interaction; $E_M$, energy of dissociation of a metallic bond; $E_A$, energy of activation for the formation of a metallic bond; $E_D$, energy of activation for diffusion; $a$, constant of a metallic lattice; $r$, distance of approach