Explosive welding of metals in a vacuum environment

Over the years, several articles have already been written on the phenomenon of explosive metal working. This is then usually taken to mean the explosive welding and cladding of metals, although explosives can also be used to shape, cut and harden the surfaces of metals. Various sources of literature provide the essentials on this subject and regular articles can be found on the development of various theories regarding the binding mechanism. It would therefore be a good idea to once again think about this remarkable welding process that also lends itself well, these days, to being performed in a vacuum environment. This last mentioned fact is particularly noteworthy as this process is normally carried out in the open air (Fig. 1). The main reason for this is that oxygen is needed to facilitate the explosion and because the explosive forces would destroy buildings. The main purpose of the article below is to describe the process of explosive welding and the cladding of metals.

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Fig. 1. Explosive cladding in the open air; also called atmospheric cladding for the sake of convenience (Photo by Innomet b.v.).

The purpose of explosive welding.

In practice, regular use is made of aggressive reagents, to which normal steel qualities offer insufficient resistance. The solution to this is to choose a high-quality metal or alloy such as stainless steel, copper and nickel alloys, titanium or zirconium etc. However, as soon as process conditions require the need for sheets or discs with significant thicknesses, the end product will become too expensive. This is particularly the case with equipment that needs to function under high pressure or in a vacuum. The solution is then to use a relatively cheap base material to which a relatively thin layer of expensive metal is bonded by means of explosive welding. This base material is often unalloyed or low alloy carbon steel. Examples are sheets used for shells and bases in the construction of reactor vessels, boilers, clad tube sheets for heat exchangers, nozzles etc. A few examples can be seen in Fig. 2.

In addition, explosive welding can be used to produce metal combinations that are impossible to achieve with a thermal welding process. Examples include the combination of steel (or stainless steel)

Fig. 2. Heat exchangers with a clad tube sheet (Photo by SMT b.v).

with metals such as aluminium, titanium, zirconium and copper. It can more or less be said that explosive welding makes it possible to produce all metal combinations that have a full metallic bond.It can be concluded that the purpose of explosive welding is to reduce the cost price of a piece of equipment whilst improving its quality. Furthermore, the final wall thicknesses will be thinner due to the benefit of the relatively high mechanical values of the steel substrate. This in turn saves on weight. In addition to saving on expensive metals, lower electrical transition resistances can be achieved with detachable bimetallic electrical contacts.

Metallic bond.

The welded joint produced with the help of explosives is based on a metallic bond. The question arises, however, of what actually constitutes a metallic bond.To sum up briefly, each metal exists as a result of this bond. A metallic bond is produced thanks to valence electrons that bind metal atoms together.These valence electrons are able to move freely through the entire metal lattice forming a shell or cloud together. This is sometimes also known as a gas cloud of free electrons, which is also the reason why a metal is able to conduct an electric current. Naturally, the atoms retain their fixed electrons around the atomic nuclei, which, by definition, are called non-valence electrons.
During the explosive welding process, a powerful shock drives the metal atoms into each other's sphere of influence, forcing the valence electrons into each other's paths. This is essentially how a metallic bond is created, the properties of which, in theory, are not inferior to those of a normal metallic bond.

Explosive welding process

In order to obtain a good idea of the processes involved, we will take the example of a carbon steel sheet which needs to be clad with a high-quality metal. After the characteristics of the materials to be clad have been assessed, the sheets are stripped of their oxide layer by means of an automated scouring process. They are then placed on top of one another at a specific distance using plastic spacers. A frame is then fitted on top of the upper sheet which will contain the powder explosives. A detonator is attached and the whole pack is ready for the explosive welding process. Fig. 3 provides an illustration of this.
Activation of the detonator triggers a powerful explosion that only lasts a fraction of a second. Picture 4 provides a snapshot of this process. Although different theories exist with regard to what actually happens during this explosion, the opinion below seems to be one of the most logical and plausible.

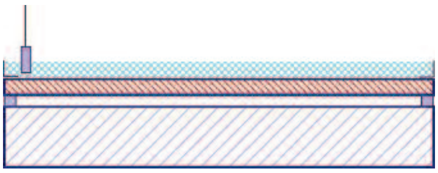

Fig. 3. Illustration of the set-up needed for the explosive welding process.

The highly explosive force drives the top plate onto the base plate at an extremely high velocity creating a collision point. At the point of collision, the pressure is so high (several thousand bars) that the metals become super-plastic in highly localised areas. There are even indications of some atomic layers briefly turning to fluid due to this enormous pressure, even though the increase in temperature is negligible.
During the explosion, a shockwave is created which is transmitted through the two metal layers in a similar fashion to ripples in water. Due to the superplasticity of the metals in the area of collision, the shockwave is able to produce a slight wave effect in the material. This wave pattern can often be seen with the naked eye where the metals join. The high velocity of this wave effect strips away any newly formed oxides on both surfaces. This can best be compared to a rug that is shaken out forcefully. The detached oxides are expelled as a flow of matter just ahead of the detonation front. This flow of matter is also known as a jet. This action leaves behind clean metal surfaces which have no time to oxidise, thereby allowing a metallic bond to be created. The bond is produced as a result of the high pressure which is still present and which causes the valence electrons to cross into each other's sphere of influence. This is how the metallic welded joint is eventually achieved. This welding process is also known as a variation of the cold pressure welding process as the entire process is carried out at ambient temperature. It will also be evident that the air between the sheets is expelled during the cladding process unless this process is conducted in a vacuum environment.

Open air cladding versus vacuum cladding

Explosive welding or cladding can therefore be carried out in the open air or in a vacuum environment. The latter is easier said than done as it first requires a special vacuum dome to be developed. In addition, it must be possible to create a sufficient vacuum in this space. There is also the problem of explosives needing

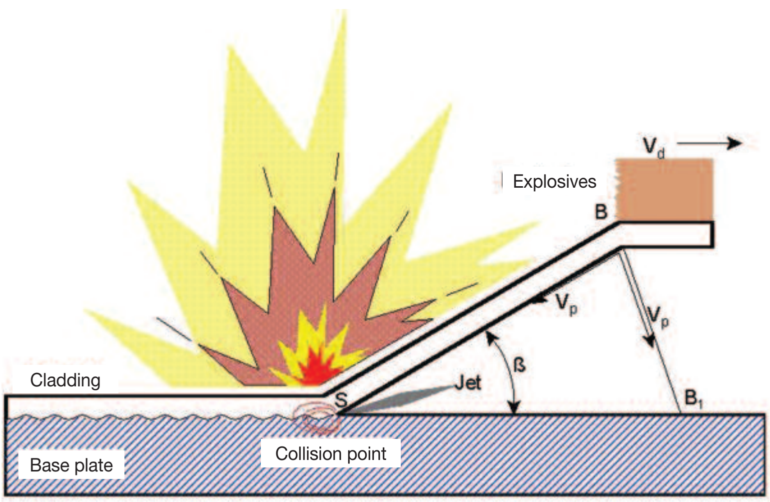

Fig. 4. Snapshot of the explosive welding process.

oxygen during the explosion. This means that special explosives need to be developed that generate their own oxygen when activated. It is clear that vacuum cladding is a far more complex process than atmospheric cladding. The question therefore arises as to why carry out this process in a vacuum environment at all. The answer to this is that it mainly has to do with the superior quality of the welded joint achieved in the end. There are also additional advantages such as being able to work regardless of the weather and a significant reduction in noise as noise requires air in order to travel. Yet another advantage is that fewer explosives are required as no air needs to be removed. Besides saving on explosives, there is another benefit which is related to the type of transition. In practice, the shockwave can result in three types of transitions - laminar, wavy or turbulent. These are illustrated in fig. 6.

If an inexperienced person were to look at these transitions, they would quickly come to the conclusion that the turbulent bond could well be the most optimum as the metals are noticeably interlocked. This would be a mistake, as the bond is not created by an interlocking process or something similar after all, but thanks to a metallic bond as explained earlier. In fact, the most attractive transition is a wavy one, but in practice the immense speed of the process often causes the peaks of the waves to top over creating a turbulent transition. This can somewhat be compared to waves in the sea which curl over when they reach a certain height. In other words, the greater the shockwaves, the greater the chance of a turbulent transition being created.

When the super-plastic waves curl over, some of the oxides from the oxide flow (jet) that is created become trapped. This leads to the development of unwanted oxide pockets or conglomerates in the wave patterns as illustrated in Picture 6. These pockets are visible to the naked eye. If a clad strip of this type were to be bent, these oxide conglomerates would open out even more. In theory, acceptable mechanical values can be achieved with these types of transitions and their shear values can be even better than for a laminar transition. The disadvantage,

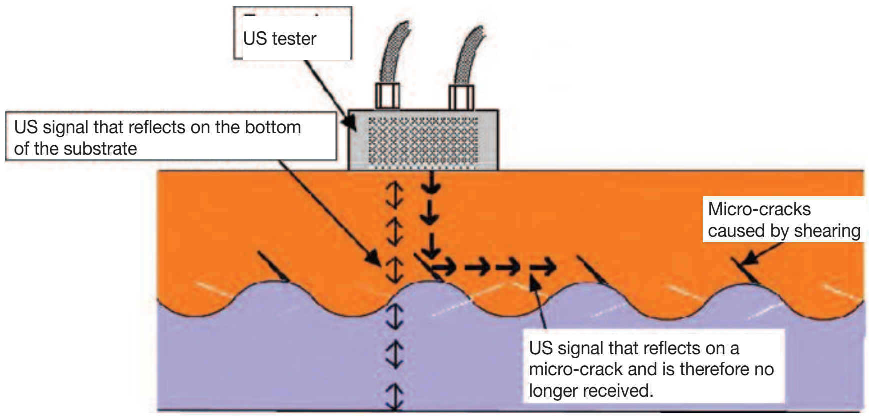

Fig. 5. US signals are dispersed by the micro-cracks that can develop on the peaks of the waves.

however, is that foreign particles have become trapped, which can undermine resistance to corrosion in certain applications. The oxide pockets are porous and are also hygroscopic which, partly due to the potential difference of the two clad metals, can accelerate the development of corrosion. This is especially the case with clad connecting strips which are used to weld an aluminium deckhouse to the steel deck of a ship. Another disadvantage is that high wave patterns can produce micro-cracks on the peaks of the waves. These are caused by internal shearing in the metal lattice. The risk is particularly high with less ductile metals.

Internal research has therefore shown that the laminar transition provides the best connection as it offers the following advantages:

- These types of transitions remain free of oxides and any brittle intermetallic connections that can develop due to extreme pressures as is the case when using a lot of explosives.
- It has also been shown that micro-cracks can develop on the peaks of waves in a high wave pattern; particularly when metals are less ductile. This is illustrated in fig. 5. An ultrasonic tester can be used to determine these cracks. This is a problem that does not arise with laminar transitions.
- As fewer explosives are used for laminar transitions, there is also considerably less strain hardening of the metal surface. It can actually be said that the structure of the two metals remain unchanged as do the other initial properties. It is evident that this also offers a significant advantage.

Fewer explosives are therefore required for vacuum cladding, which means that, in principle, a laminar or slightly wavy transition is achieved. No oxide pockets develop in this case as these oxides are able to escape in time. An additional advantage is that tests have shown that fatigue strength is also superior. This is why the offshore industry, in particular, prefers using vacuum clad connecting strips to strips produced in the open air. This also applies when these strips are used asymmetrically in ship building as they are better able to absorb torque forces. This is all due to the absence of micro-cracks in the wave peaks.

US tester

US signal that reflects on the bottom of the substrate

US signal that reflects on a micro-crack and is therefore no longer received.

Micro-cracks caused by shearing

In order to check an explosion weld, a 'Hammer Bend Test' can be carried out in accordance with the MIL-J-24445A norm. A narrow strip of clad metal is clamped on the metal transition joint in a bench vice. The protruding part is then bent 90º with a hammer. It will not be difficult to understand that oxide pockets will open as a result. This disadvantage does not occur with a laminar transition created during vacuum cladding. An example of this can be seen in Fig. 7. Any micro-cracks in the peaks of the waves will also have a detrimental effect.

Testing

The edges are removed from every clad sheet as interference and reflection on the periphery makes it impossible to create a good connection. The sheets are then aligned and fully tested with an ultrasonic examination. In addition, the mechanical values are determined in accordance with the standards laid down. Most clad products also undergo an acceptance test performed by an independent inspection agency. This results in the required documents and certificates.

Applications

As mentioned earlier, applications are mainly found in the heavy machine building industry. In particular, tube sheets for heat exchangers, shells for reactor vessels and so on can be manufactured effectively using explosive cladding. fig. 9 shows a heat exchanger with a clad tube sheet and a clad shell in front of this. The materials are carbon steel clad with super duplex. Further, this type of joint can also serve as a starting point in the manufacture of roller clad plates. It is also used to make transition joints which are sawn from sheets as strips. These strips can be used in the shipbuilding industry, for example, to weld an aluminium superstructure to steel decks. Not only does this save on rivets or nuts and bolts but also minimises the risk of corrosion.

Electrolysis companies that reduce primary metals from ores often use aluminium anode rods that need to be connected to steel or copper. Aluminium is a good conductor of electricity but as the temperature in the vicinity of the electrolytic cell is too high, a steel frame connected to the carbon block is required in this area. By welding a cladding between the steel and aluminium, there will be no transition resistance.

If aluminium is connected to aluminium mechanically, then this results in a transition resistance because of the oxide layer. Copper does not have this and this can therefore lead to substantial savings on energy bills. These types of connections are preferable as these contacts must be detachable.

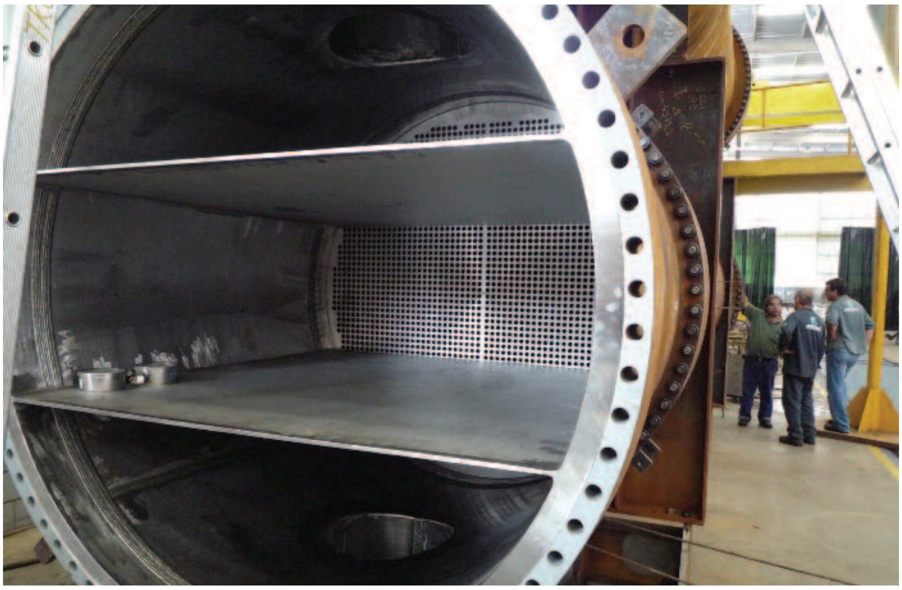

Fig. 9. A heat exchanger with clad tube sheet and shell. The base is carbon steel and the cladding is super duplex (Photo by SMT b.v.).

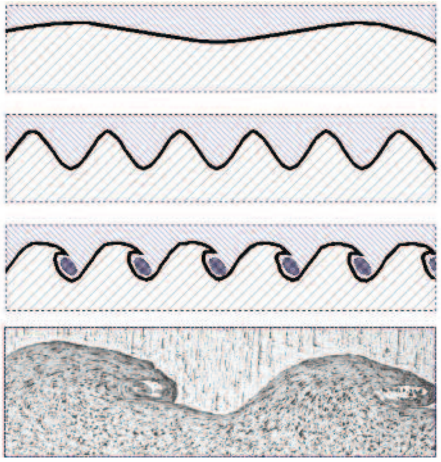

Fig. 6. Three types of transitions resulting from explosion welding - laminar, wavy and turbulent. Sometimes the waves can even tip over as shown in the photo.

Conclusion

This article provides a summary of the explosive welding process, in both an atmospheric and a vacuum environment. Although it shows there are significant differences between the two, it must not be concluded that open air claddings will turn out to be inferior. Vacuum cladding does, however, bring specific properties to the fore which will eventually prove to be advantageous. One company that performs vacuum cladding is SMT b.v. in the Netherlands.

For more information please contact: info@innomet.nl, or visit www.triplate.com and www.smt-holland.com.

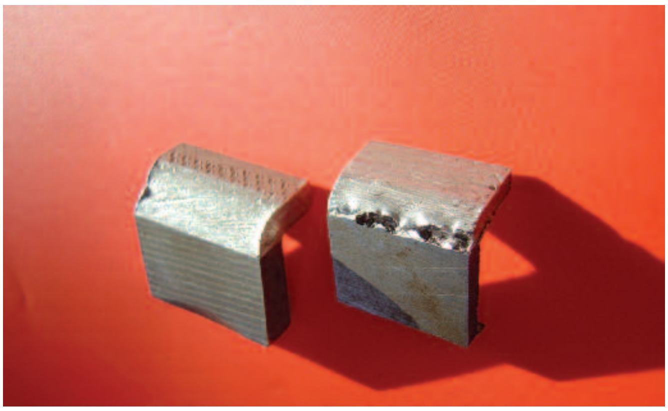

Fig. 7. The consequences of the 'Hammer Bend Test'. On the left is a vacuum cladding and on the right a cladding produced in the open air. The oxide conglomerates open out as a result (Photo by Innomet)

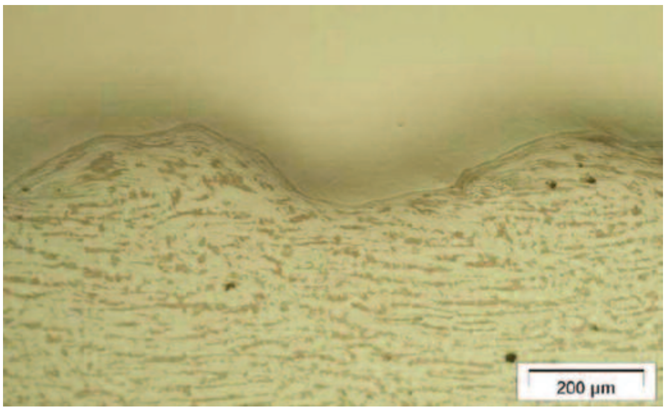

Fig. 8 Perfect waving interface without any turbulence or oxides.