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ADVANTAGES AND APPLICATION POSSIBILITIES OF ADHESIVE BONDING

1. INTRODUCTION

The requirement for minimising the energy and material consumption, as well as the tendency to reduce structure weight, place the utilisation of new materials and design improvement on the first place. On the contrary, in structure design, the production method comes second, which imposes high demands on the production. This is particularly true for bonding technologies, since:

- newly developed materials are most often unsuitable for joining,
- dissimilar materials have to be joined together,
- complex structure forms make the joint sites difficult to access,
- the joining spots require multiple tasks: e.g. uniform load transfer, sealing, etc.
- the requirements for loading capability and reliability are increasing.

Therefore, in some segments the conventional joining technologies such as welding and soldering will be gradually replaced by new and better developed ones such as adhesive bonding. The versatility of bonding methods will make the designer's task an easier one, when acquiring knowledge about the possibilities of replacement and about the limitations of certain bonding methods.

Compared to other bonding methods, e.g. welding and soldering, adhesive bonding has a range of advantages: uniform load transfer (no stress concentrations), ability to join dissimilar materials without structural changes of the joined materials, electrical and thermal insulation, inherent sealing characteristics, and vibration dampening, as well as good sound dampening. The limiting factors in applying adhesive bonding are, firstly, poor joint strength, especially with fatigue and thermal effects on the joint. A disadvantage is also limited (expensive and complicated) testing of adhesive bonded joints. Moreover, some additional reasons for not using adhesive bonding include very often the required complicated surface preparation, which along with the time needed for adhesive hardening prolongs the technological process and requires additional investment costs as well as the need for maintaining the adhesive bonded joint after joining.

2. SYSTEMATISATION AND EVALUATION OF JOINING METHODS

Over the recent years various valuable models for systematisation and selection of joining methods have been devised [1,2]. Because of the multiplicity of joint types and properties the selection of the optimal joining process follows a very complicated process. For the presented study of comparing the adhesive bonding with other bonding technologies, a limitation on several selection criteria has been made. For the selection of the joining type, the evaluation of the features for the given joining is especially important with regard to:

- material and shape of parts to be joined,
- mechanical and special joining properties,
- technical and economic features,
- quality assurance and safety measures at work,

which is presented in corresponding tables.

Questions regarding re-using and recycling have not been specially evaluated, since these properties correlate to the possibility of disassembling the joints. The bonds that can be disassembled offer better possibilities for re-usage by dismantling. The joints that can be disassembled compared to those that cannot, are easier to sort regarding the sorting procedure for recycling.

The evaluation was performed according to a scale of 5 grades, and for the sake of visual distinction the following symbols were used:

● very suitable
◕ suitable
◑ moderate
◔ unsuitable
○ not advisable

The symbol "not advisable" means that a certain technology is not capable of fulfilling the given requirements. In many cases no improvement of certain features through additional measures is given, e.g. providing sealing properties of a screw joint, riveted joint or spot welding, by using sealing agent.

For the selected evaluation criteria and for assessment, some limitations are also presented. The evaluation criteria are in no way complete, but present only a selection of opposing demands which are set by design. In single cases some further requirements which have not been presented here may be decisive in selecting the joining method.

The listed evaluations do not lie only under the subjective influence, but neglect the existing interaction between certain specific influences. So e.g. the productivity of one procedure may be influenced both by the material and by the shape of the workpiece.

3. SYSTEMATISATION AND EVALUATION OF ADHESIVE BONDING PROCESSES

Adhesive bonding is a solid type of joining, and the load transfer is provided over the material surface.

As a rule, the adhesive bonded joints are regarded as joints that cannot be disassembled since in the majority of applications, especially with very strong joints, disassembling of the joint is possible only by rupturing the adhesive layer. On the contrary, the adhesive tapes can after rupturing of the joints be reused as adhesives. With conditioned disassembling of joints, usually the reinforcement of screwed joints by adhesion is meant, where the use of an appropriate solvent may regulate the adhesive strength, thus enabling the joint disassembling and the use of the same adhesive for renewed reinforcement of the joint (micro-enclosed adhesives). Heat can disrupt the bonded joint without damaging the joined materials, especially with fusion adhesives.

The known advantages of adhesion include the possibility of joining dissimilar materials without changing the structure of joined materials, uniform transfer of load, good sealing conditions, good dampening of vibrations and noise, as well as good electrical and thermal insulation. The limiting factors are: limited strength of the joint, especially at higher temperatures and fatigue, and adverse methods of testing the adhesive bonded joints. High investment costs for preparing the surface, price of the adhesive, duration of the process and the demanding protection at work also speak against this bonding technology. Table 1 shows advantages and disadvantages of adhesive bonding regarding the selected evaluation criteria. The proper selection of adhesive type depends on the requirement specification, which should include:

- materials to be bonded by adhesion and surface condition
- measurements and joint designs
- the required time of production, magnitude and direction of main stresses
- ambient temperature
- relative dampness and presence of chemicals.

Joint designs modified for adhesive bonding avoid "linear" load such as e.g. peel strength. With parts of high strength, such as metals, the lap joints are preferable to butt ones, since the increase of lap surface supplements the lower strength of adhesive with the higher strength of the parts to be bonded by adhesion.

The load capacity of adhesive bonded joints depending on the temperature and load (static and dynamic) will depend on the following parameters: type of material to be joined, joint geometry, surface condition, application and adhesive properties of adhesives, cohesion balance, and possibilities of variable adhesive shape, thickness of the adhesive bonded joints, fatigue and chemical resistance. Fatigue of adhesive bonded joints is of great significance, since depending on the time the strength decrease could cause a premature rupture of the joint.

The calculation methods for predicting the behaviour of adhesive bonded joints should correspond better to the actual situation. The main problem in dimensioning includes the uneven strength of adhesive as well as difficulty in foreseeing long-term changes because of fatigue.

As adhesives can be successfully applied in certain fields, such as fitting glass windows in cars, the adverse negative side-effects prevail in other fields. Careful testing of the adhesive, cautious preparation of surfaces and appropriate adhesive bonding technology, as well as the properly skilled personnel form a prerequisite for producing high quality adhesive bonded joints. When these hypotheses are not met, a premature rupture of the joints can be expected.

4. COMPARISON OF ADHESIVE BONDING AND "COMPETITIVE" JOINING METHODS

The most important technologies that can be considered as "competitive" to adhesive bonding are welding, soldering, riveting, bending (flexing) and screw fastening. Within these, the welding technology consists of numerous and different processes which can be replaced to a greater or lesser degree with regard to the concrete joining procedure by adhesive bonding.

Table 1 - Advantages and disadvantages of adhesive bonding regarding the selected evaluation criteria

Evaluation criterion	Grading	Explanation
Type of material	●	Metals, plastics, ceramics, various combinations
Thickness of material	◕	From foils to thick cross-sections
Shaping	◕	From small to big surfaces
Type of joint	◑	Mainly lap joints
Loading	◑	Avoid peel strength loading
Static loading capacity	◕	Depending on the adhesive type and lap
Resistance to elevated temperatures	◔	Depending on the type of adhesive
Resistance to corrosion	◑	Fatigue (dampness and UV radiation)
Weight, required space	◕	Lap
Form of joint	◕	Lap
Accuracy of forms	◕	Depends on adhesive shrinkage
Sealing	◕	Conditionally liquids and gases
Dampening	◕	Oscillation and noise
Possibility of disassembling	◑	By heating
Additional functions	◑	Electric and thermal insulation
Productivity	◑	Preparation, hardening
Automation	◕	Producing multiple joints simultaneously
Preparation cost	(1)	Recommended preparation of surface
Joining cost	◑	Application, fixing, reinforcement
Materials cost	◔	Adhesive, chemicals for surface preparation
Post-machining cost	◕	Possibly to clear the adhesive rests
Production monitoring	◔	Numerous influencing values, difficult to measure
Non-destructive testing	◔	Long-term behaviour and adhesion force values, difficult to measure
Repair	◑	Rupturing of joints, cleaning
Safety at work	◑	Possibility of fire
Health protection	◔	Emission of harmful particles and absorption through skin

(1) Depending on materials and requirements:
Materials: steel, thermosets (degrease, grind)
Adverse: polyolefin (chemical, electrical and thermal surface preparation)

● Very suitable ◕ Suitable ◑ Moderate ◔ Unsuitable ○ Not advisable

4.1 Electric Arc Welding

Electric arc welding procedures are most often considered as the alternative to the adhesive bonding technology.

Compared to adhesive bonding, the joining capability of dissimilar materials and their combinations is limited. However, the possibilities of shaping the joint are better. Also, arc welding procedures gain significant advantages due to the resistance of the welded joint towards peel strength, vibrations damp and aggressive media. A significant drawback of joining two materials by welding is the high supply of heat into the joint. Regarding production, the adhesive bonding technology requires higher initial costs because the surface needs to be prepared. Quality assurance is more difficult to achieve with adhesive bonding than with welding, because it requires the application of climatic tests and because the non-destructive methods do not provide reliable clarification about the magnitude of adhesive forces. Regarding safety at work, both bonding procedures are disadvantageous.

4.2 High Power Density Beam Welding

Electron jet and laser welding are (like electric arc welding) fusion welding processes. Numerous metals can be welded, graphite and ceramics joined, but not polymeric materials. Due to high power density, the heat supply is short and limited. Therefore the heat induced stress is low so that parts of small dimensions can be welded. High welding speeds and the possibility of welding thick parts by electron jet result in high productivity. The preparation costs are due to the required minimal tolerances very high, as well as the cost of the process itself, with significant cost for the amortisation of equipment. The possibility of quality assurance by monitoring the process and non-destructive testing is better than with adhesive bonding. Regarding safety at work, the rules have to be obeyed because of laser beam and X-ray radiation (electron jet welding).

4.3 Electric Resistance Lap Welding

This group includes the processes of spot, projection, and seam electric resistance welding that is carried out by forming welding spots or lines at lap joints.

Compared to adhesive bonding the selection of materials is limited. Significant advantages are high joint conductivity and resistance to high temperatures; the sealing of joint is provided only with seam welding. A disadvantage compared to adhesive bonded joints is the risk of corrosion and poorer possibility of vibration dampening.

Regarding production cost, the electric arc welding is preferred to adhesive bonding, particularly in preparation and cost of material. Quality assurance is difficult in both cases due to difficulties in performing the non-destructive tests.

4.4 Electric Resistance Butt Welding and Friction Butt Welding

To weld bars, pipes, and other profiles, various processes have been developed, primarily the electric resistance welding with pressure (butt welding with pressure and sparking) and friction welding. With electric resistance welding with pressure, different profiles can be butt welded, whereas with friction welding at least one of the workpieces has to have a cross-section with approximately rotational symmetry. On the other hand, friction welding provides the possibility of welding a big number of metal combinations, that are otherwise difficult to join.

The advantage over adhesive bonding lies in the high joint strength, capability of supporting high static loads, and better conductivity of electricity. Higher productivity and automation facility add up to advantages, and the preparation costs are also more acceptable than with adhesive bonding. The production cost depends on the different high prices of equipment. Post-machining is generally required, to eliminate bulges, and non-destructive testing is better than with adhesive bonding.

4.5 Welding of Polymers

Only thermoplastics are suitable for welding. The most important processes are welding by heating elements, hot gases, extrusion welding, ultrasonic welding, rotational welding, vibration welding, as well as high frequency welding. These differ in the capability of welding various thermoplastics, geometry of the workpieces to be welded, type of welding joints (butt, lap), and the size of the welding surface, so that a suitable welding process can be selected according to the mentioned properties for the required joining of materials. Compared to adhesive bonding, the advantage most often lies in lower preparation costs, and in the safety at work. On the contrary, the required pressing results in distortion from given measurements and therefore the formed bulges require post-machining.

4.6 Soldering

Due to specific features of soldering there is no single criterion according to which the processes could be classified. Therefore e.g. the following criteria are applied:

- working temperature (soft and hard soldering)
- shape of the joint (capillary soldering, groove soldering, soldering by brushing)
- heating means (gas, induction, oven, etc.)
- type of protective atmosphere (air, protective gas, vacuum)
- oxide removal during soldering (flux, reduction gas, vacuum, etc.)

Soldering is suitable for joining dissimilar metals, and ceramics can be soldered as well. It is also possible, by selecting the suitable solder, to join various combinations of metals.

The loading capability of soldered joints made by soft soldering is low, therefore such soldering is suitable for low loaded joints, e.g. joints made for conducting electricity. Therefore, brazing is more suitable for comparison with adhesive bonding. The strength of joint achieved with brazing is moderate to high. The temperature resistance depends on the difference in melting points of the base and filler material. Capillary filling of the joint requires accurate preparation. The cost of soldering material and flux is very high, especially when precious metals are used.

By suitable production planning high productivity and automation can be achieved. Non-destructive testing and visual control can provide quality assurance. Regarding safety at work, solders containing cadmium and fluxes containing fluorine should be avoided.

4.7 Riveting

Riveting, similarly to adhesive bonding, can be used to join almost all structure materials, various material combinations. On the contrary, the type of joint is limited to lap joints. Regarding behaviour of joint by static and dynamic loading, adhesive bonding is preferred; riveted joint shows better resistance to higher temperatures. Corrosion resistance is limited due to the joint clearance, and besides there may be an adverse difference in potential of the rivet and the base materials. A riveted joint conducts electricity, an adhesive bonded joint provides sealing. With bigger surfaces to be joined the productivity is greater with adhesive bonding, with smaller surfaces riveting is better. The costs of drilling bores, rivets and riveting are higher than the cost of adhesive bonding. Adhesive bonding has advantages in quality assurance and safety at work.

4.8 Joining by Flexing

Flexing (bending) is one of the most frequent methods of joining sheets in air-conditioning as well as in manufacturing doors in automotive industry. Regarding joined materials, joint design and loading, this process is limited in comparison to adhesive bonding. Also, with static and dynamic loading flexing is less suitable than adhesive bonding. The advantages over adhesive bonding lie in higher productivity, lower preparation and production costs, good joint testing and the required lower level of safety at work.

4.9 Screw Fastening

The process is, like adhesive bonding, suitable for joining dissimilar materials of various thickness, but regarding shaping possibilities it is certainly limited. Behaviour in oscillating loading is worse than with adhesive bonded joints, and with higher temperatures the screw joints are far more suitable. The main advantage is that it can be easily disassembled and easily repaired. A disadvantage compared to adhesive bonding is poor sealing capability and high cost of material. Regarding testing of joints and safety at work, screw fastening is more suitable than adhesive bonding.

4.10 Comparison of Joining Processes

Table 2 presents the comparison of all the mentioned joining processes. In comparison to competitive processes, the advantages of adhesive bonding lie in the possibility to join different materials of different thickness, good dampening characteristics, and good shaping possibilities. The disadvantage lies mainly in low resistance to high temperatures and a big decrease of strength with fatigue as well as high production costs, difficult quality assurance and problems with safety at work.

5. SOME EXAMPLES OF ADHESIVE BONDING APPLICATIONS

5.1 Aerospace Industry

Adhesive bonding is used in aerospace industry for manufacturing of aircraft fuselage of aluminium alloy AlZuMgCu which is unsuitable for welding. Also, the light components are bonded by adhesion, e.g. adhesive bonding of outer shells to adhesive bonding of sheet reinforcements. Also for joining of glass and carbon fibre reinforced plastics, as well as for laminar and honey-comb materials, adhesive bonding is used. Finally, there is the possibility of adhesive bonding of metals with polymers, e.g. between metals and reinforced polymeric laminates, as well as sheets and polymeric honey-comb materials (e.g. rudder).

Because of unsuitability for welding and soldering as competitive methods, the most frequently used alternative is riveting, whose advantage compared to adhesive bonding lies in lower production costs (no surface preparation), in better long-term behaviour of joints, and in better maintenance. The advantages of adhesive bonding lie in creating a joint of lower resistance to airflow as well as in the possibility of generating shapes which are difficult to join, e.g. between sheet covers and cores for honey-comb elements.

5.2 Automotive Industry

In automotive industry the steel sheets are adhesion bonded with steel profiles for reinforcement of hood and trunk lid. The advantage over the conventional electric resistance spot welding is better noise and oscillation dampening, the possibility of greater joint clearance tolerances and avoiding pressure on the surface and consequently the expensive post-machining. Furthermore, adhesive bonding is used for attachment of accessories to the car-body, e.g. lid of the sliding roof, petrol cap. The advantages compared to mechanical bonding are better sealing, smooth surface contour, and reduced possibility of rupture due to corrosion. To increase strength adhe-

Table 2 - Comparison of joining technologies

Evaluation criterion	Adhesive bonding	Electric arc welding	High power density beam welding	Electric resistance lap welding	Electric resistance butt welding and friction welding	Welding of plastics	Brazing	Riveting	Flexing	Screw fastening
Type of material	●	◑	◑	◑	◑	◔	◕	●	◑	●
Thickness of material	◕	◕	◑	◑	◑	◑	◕	◑	◔	◕
Shaping	◕	◕	◑	◑	◔	◕	◕	◑	◑	◕
Type of joint	◑	◕	◕	◕	◔	◕	◑	◔	◔	◑
Loading	◑	●	●	◕	●	●	◕	◑	◑	◕
Static loading capacity	◕	●	●	◕	●	◕	◕	◕	◑	◕
Dynamic loading capacity	◑	◑	◕	◑	◕	◑	◑	◑	◔	◔
Resistance to elevated temperatures	◔	●	●	●	●	◕	◑	◕	◕	●
Resistance to corrosion	◑	◕	●	◑	●	●	◑	◔	◑	◑
Weight, required space	◕	◕	●	◕	◕	◕	◕	◑	◑	◔
Form of joint	◕	◕	◕	◑	◑	◕	◕	◑	◑	◔
Accuracy of forms	◕	◔	◕	◑	◑	◑	◑	◕	◕	◕
Sealing	◕	●	●	◑	●	●	●	◔	◑	◔
Dampening	◕	◕	○	◔	○	◕	◕	◔	◔	◑
Possibility of disassembling	◑	◕	◔	◔	◔	◔	◑	◔	◔	●
Additional functions	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑
Productivity	◑	◑	◑	◕	◕	◑	◕	◑	●	◔
Automation	◕	◑	◕	◕	●	◕	◕	◕	●	◑
Preparation cost	◔	◑	◔	◕	◕	◕	◔	◑	◕	◔
Joining cost	◑	◑	◔	◕	◑	◑	◑	◑	◕	◔
Materials cost	◔	◑	◕	◕	◕	◕	◔	◔	◕	◔
Post-machining cost	◕	◑	◔	◕	◑	◕	◕	◕	●	●
Production monitoring	◔	◔	◕	◔	◑	◑	◑	◕	◕	◕
Non-destructive testing	◔	◕	◕	◔	◑	◑	◑	◕	◕	◕
Repair	◑	◑	◔	◔	◔	◔	◑	◔	◔	●
Safety at work	◑	◔	◑	◕	◑	◕	◑	●	●	●
Health protection	◔	◔	◑	◑	◑	◑	◑	◕	◕	●

● Very suitable ◕ Suitable ◑ Moderate ◔ Unsuitable ○ Not advisable

sive bonding can be combined with spot welding or riveting. Adhesive bonding of steel profiles in combination with flexing is used for joining of inner parts of doors with the outer body. The advantage compared to the conventional spot welding and independent flexing is elimination of corrosion in the joint clearance due to the good sealing qualities of adhesives, better rigidity as well as better dampening of noise and vibrations.

The possibility of joining metals with polymeric materials is used with adhesive bonding of plastic containers for spare wheels with steel bottom, plastic shell with body, plastic roof on smaller cargo vehicles, as well as fastening of plastic side struts. Adhesive bonding of metals with glass is used in fitting front, rear and fixed side windows and has almost completely replaced the fitting with rubber holders. The advantage of adhesive bonding lies in the smooth contour (better Cd value), as well as increase of the overall car-body strength. The disadvantage lies in the greater difficulty of replacing windows in case of repair.

5.3 Adhesive Bonding in Mechanical Engineering

The advantages of adhesive bonding of shafts - hubs are: there is no need for "strict" tolerances, axial fixing, simple mounting (no heating), avoiding corrosion in joint clearance, proper stress and shear effect. The disadvantage is possible contamination by leakage of adhesive, difficult disassembling (thermal extrusion), low resistance to high temperatures, and possible fatigue. Adhesive bonding of bearings eliminates also the requirement for "strict" tolerances, simplifies the mounting, eliminates stresses that are generated by the "conventional" installation of bearings and results in better noise and vibration dampening. The disadvantage is difficult replacement, removal of extruded adhesive, and possible fatigue. The reinforcement of screw joints by adhesive bonding provides better safety against nut loosening than the mechanical safety elements, protects threads from corrosion and seals also with through-threads. The disadvantage is the damaging of the thread by repeated disassembling, limited strength at higher temperatures and possible fatigue.

Further typical example of adhesive bonding in mechanical engineering is fixing of braking and lamellar lining, manufacturing of rubber and metal vibration dampers, as well as manufacturing of joints that provide good sealing due to adhesive bonding.

5.4 Adhesive Bonding in Electrical Industry and Precision Parts Industry

In these fields of application adhesive bonding is used because of the following properties:

- possibility of joining dissimilar materials, e.g. metals with polymeric materials;
- possibility of joining pressure and temperature sensitive materials, e.g. for fixing semi-conducting elements to printed electronic boards;
- high accuracy (no thermal stresses);
- possibility of varying electrical and thermal properties by using filler in the adhesive;
- protective function and good sealing properties;
- versatility, e.g. mechanical joining, insulation from dampness and electricity by adhesive bonded sheet lamellas for transformers and relays etc.

Disadvantage of adhesive bonding is possible fatigue and limited electrical conductivity.

6. CONCLUSION

Although adhesive bonding is a very old method of joining materials, the technology of adhesive bonding is one of the youngest joining technologies. The reason certainly lies in the low strength, even of today's adhesives, compared to metal materials and the lack of knowledge regarding the time of weakening of adhesive forces in adhesive bonded joints. However, adhesive bonding does have a number of advantages. Certainly, the most important are the possibility of joining dissimilar materials, slight thermal effect on the joint and bonding without damaging the material.

The increasing number of materials that are difficult to join, more and more requirements for keeping the given tolerances, as well as the tendency to versatility, such as e.g. uniform transfer of loading, sealing, vibration dampening, allow optimistic expectations regarding further increase in adhesive bonding applications.

SUMMARY

The paper deals with some advantages and disadvantages of adhesive bonding compared to concurrent bonding technologies, as well as possibilities of applying adhesive bonding in joining of materials. The listed joining methods are compared to adhesive bonding, and the evaluation criteria for each process are given.

Some examples are presented regarding adhesive bonding application in automotive, aerospace and electrical industries.

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