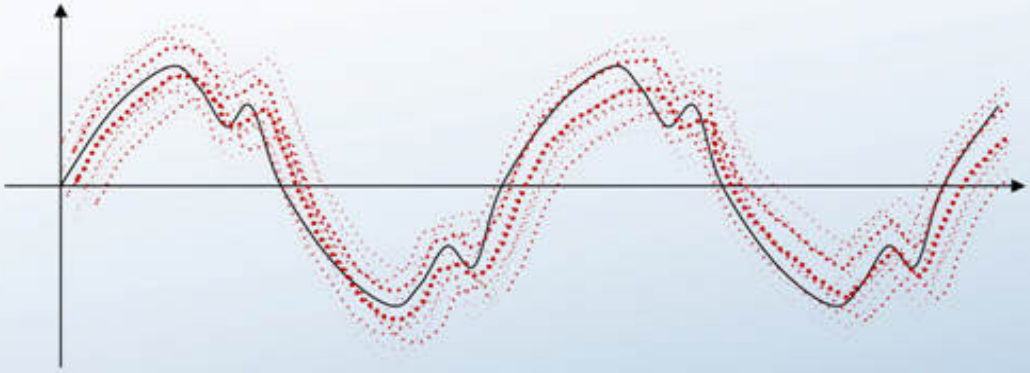
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LOUSY WAVES

How to track down flaws in the ultrasonic welding process

A guide for practitioners...

Dear readers…

… an unnecessary service call is annoying and expensive!

Familiarize yourself with our small practical guide for specialists in ultrasonic treatment of thermoplastic materials. It contains lots of useful information that will help you decide what to do. We'll show you how you can easily and quickly see the quality of sonotrodes and the overall welding process and act accordingly.

We wish you good luck – and we are always happy to help you with any questions.

Yours
FEINTECHNIK
R.Rittmeyer GmbH

© FEINTECHNIK
R.Rittmeyer GmbH
Höltenweg 103
48 155 Münster
Germany

Telefon ++49 (0)251 . 96 115 – 0
Telefax ++49 (0)251 . 62 45 25
E-mail: rittmeyer.beri@t-online.de
Web: www.rittmeyer-beri.de
www.sonotrodenbau.de

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1 Introduction

1.1 Preliminary remarks

Thermoplastic parts, foils and fabrics have been molded for decades using ultrasonic techniques. The “classical” ultrasonic processing tasks include joining by welding, riveting, crimping, embedding, cutting, separating and punching.

However, recent years have seen the addition of many new applications, such as boring in brittle materials (e.g. glass) or - in the cosmetic-medical area - micro-massage for treatment of skin diseases by stimulating blood flow, etc.

All that these procedures have in common is the use of welding tools called “sonotrodes”. Sonotrodes are metallic bodies that pull in a high frequency. Resonance vibration can be added. The contact of this tool with a workpiece (usually a thermoplastic) finally leads to the intended processing.

Since the entire process of ultrasonic processing is very complex and many aspects have to be considered, errors can occur at any point in the process. This guide will help you to track such errors in practice, with emphasis on the evaluation of the quality characteristics of the sonotrode and its impact on the welding process.

The guide is the result of our experience in sonotrode development and optimization, together with our practical advisory activities, and was written explicitly for the practitioner. As such, it does not contain any extensive discussion of mathematical - physical relationships.

Furthermore, it focuses on the most common ultrasonic applications, such as joining using ultrasound.



This guide is not suitable for the construction of sonotrodes. It is merely for rapid detection of faults in the welding process.

In the text we refer several times to our own Amplitude and Frequency Measurement device AFM 9.3, and we acknowledge taking the opportunity for self-promotion. On the other hand, as of August 2013 there is to our knowledge no comparable device in the world that can be used in on-site processes for ultrasonic systems as well as fast, easy, and inexpensive quality tests of ultrasonic welding processes and especially the quality of the sonotrodes used.

In Parts 1 – 4 we describe the basic working principles and tools for ultrasonic (US) welding. In Part 5 we describe the most common faults and how to detect and eliminate them.

Author's note:

This guide is not finished: it will be revised and expanded in the future. Therefore, your suggestions are very welcome. Please write us if you wish to see further topics addressed, give us tips, or identify any errors.

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Walter Rittmeyer

Münster, August 2013

1.2 Definition of ultrasonic welding

“Ultrasonic welding” of plastics means: *the firm joining of thermoplastics by melting the material by introducing a high-frequency mechanical vibration.*

Metals can also be joined by ultrasound, but are clearly far more limited in the variety of applications. The most widespread use of metal welding so far is the compaction of cable strands together or with small contact plates.

Additional applications today that fall under the term “ultrasonic welding", but which are not actual welding work in the narrower sense, include the cutting of frozen food by vibrating sonotrodes, separation from rubber, etc.

1.3 Functional principles

An ultrasonic generator generates the required voltage of several hundred volts and a desired operating frequency (usually between 15,000 and 70,000 Hz), and can provide power up to several kilowatts.

The high-frequency voltage is applied to a **converter**, in which there are ceramic piezoelectric members or transducers. The piezoelectric elements convert the applied electrical voltage to a mechanical deflection of a certain amplitude (oscillation width) in exactly the frequency which is provided by the generator. This mechanical deflection is transmitted from the converter into the booster.

The **booster** transforms the amplitude thanks to its shape and forwards the (usually greater) amplitude further into the **sonotrode**. Often the booster serves as storage for the welding unit.

A sonotrode (or horn) is typically constructed so that it amplifies the provided amplitude, because most plastics can be processed only with a relatively large amplitude (> ca. 20 µm).

The converter, the booster and the sonotrode form the **welding unit** (also “vibrating unit”).

The material to be processed is supplied to the welding unit by means of a **support and feed mechanism**.

1.4 Applications

Ultrasonic welding is considered wherever small- to medium-sized thermoplastic plastic parts must be connected. It is one of the most widely used joining methods for thermoplastics.

1.5 Advantages of ultrasonic welding

The US welding procedure offers a number of advantages, of which the most important are:

short cycle times	the sheer weld times (without feeding) are often in the range of tenths of seconds
low cost	compared to other joining techniques such as vibration welding, hot plate welding, etc.
easy to use	the welding process itself is automatic, and operation of the machines can be learned quickly
production safety	in general, the production itself is reliable and easily verifiable
large variety of processes	welding, riveting, crimping, embedding, cutting, separating, forming, and punching are all possible with ultrasound
environmentally friendly	there is no need for another medium (such as when gluing)
high strength in the joint zone	the joining zones themselves are often stronger than the surrounding material
homogeneity in the joint zone	a good weld results in a very homogeneous material zone
easy to automate	the welding unit is easy to handle and can be used in special machines or in robotics
variety of joint zone designs	depending on the plastic used, very different joint zones can be chosen
low energy consumption	compared to other joining techniques such as thermal methods, vibration welding and laser welding
non-separable material composite	US welds can not be separated again without destruction - an often desired protection for internal components

2 Machines and processes

2.1 The construction of a standard ultrasonic welding machine

Generally, ultrasonic welding machines consist of a **controller**, a **generator**, a **feed unit** moving on the **guiding column**, the **welding unit** (consisting of converter, booster and sonotrode), an **anvil** or absorption part, and the **base plate** of the press.

Figure 1 shows a standard welding press, as very often used for a single workstation with manual operation.



Figure 1 Standard Ultrasonic Welding Press, 40 kHz

2.1.1 Other ultrasonic welding machines - equipment and applications

Ultrasonic welding applications have evolved over the past decades to conquer new markets and have found their way into many new sectors. Accordingly, the machine technology has evolved and adapted to the respective applications. Other examples are:

- Rivets or spot welding with manual welding equipment



Figure 2 Manual welding device

- The welding of foils or fabrics by means of rotating sonotrodes. Over in the ultrasonic frequency a pulsating radial surface may weld or cut fabric as necessary.

Welding surface of the sonotrodes:

- different widths of the welding surface
- different surface coatings

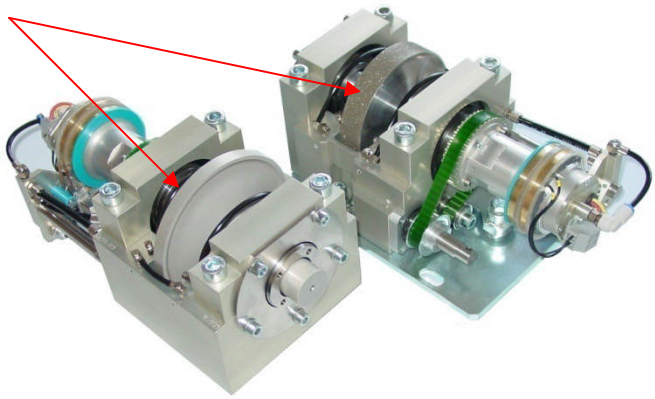


Figure 3 Rotary heads with rotating sonotrodes

Sonotrode from the side in the rotary head

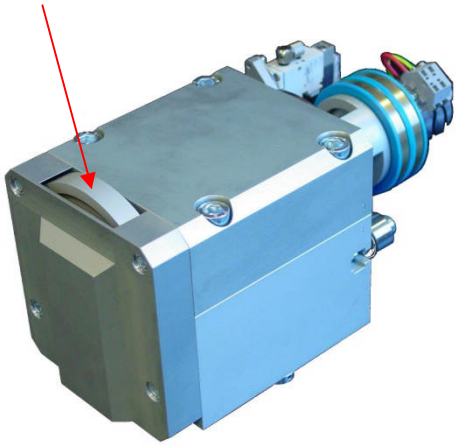


Figure 4 Rotary head with lateral sonotrode

Rotary heads are used for welding and cutting of thermoplastic films and fabrics. The ultrasonic waves are opposite to those of other sonotrodes, effectively “crosswise”.

The particular challenge in the design of rotating sonotrodes is to produce uniform amplitude, as constant as possible over the entire circumference.

Welding surface of a rotating sonotrode

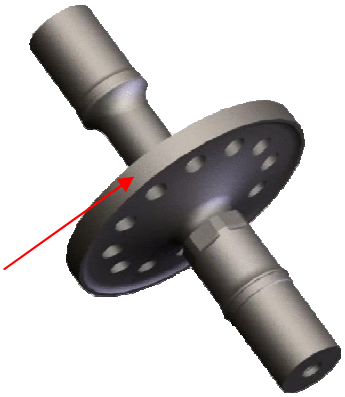


Figure 5 Rotating sonotrode

2.2 The generator

The generator is used to power the converter. It creates a voltage of several hundred volts with a frequency of 15-70 kHz. Usually the generator is accommodated in its own, separate housing.

Generators are available in a variety of power levels, which range from a few hundred watts to several kilowatts. The welding application is decisive for selection: whether a continuous weld is required (such as in film welding), how much energy is needed at the joint zone, and whether the generator should have an amplitude control are all questions that need to be resolved before purchase. Each manufacturer is there to help you make the right choice.

2.3 The feed unit

The feed unit guides the welding unit to the corresponding workpiece with the required contact pressure. In special machine constructions a variety of parallel-employed and working feed units are used.

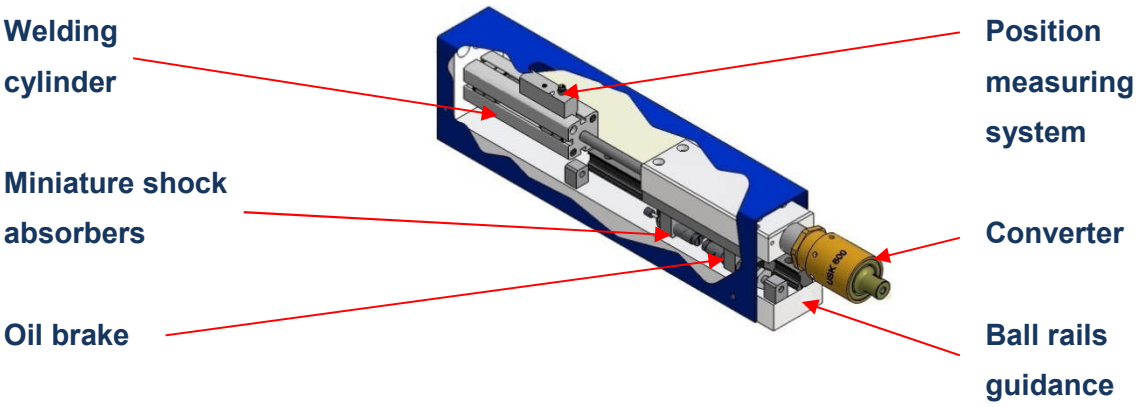


Figure 6 Feed unit for special machine

2.4 The welding unit

The welding unit consists of the converter, the booster and the sonotrode.
The sonotrode is the welding tool with direct contact to the workpiece.

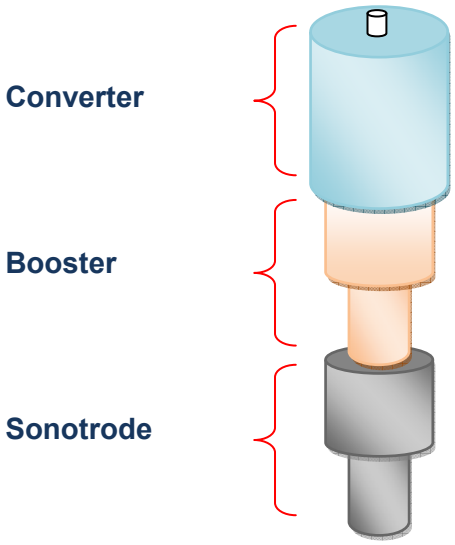


Figure 7 Basic structure of the welding unit

2.4.1 The converter (ultrasonic transducer)

Converters[1] (also: ultrasonic transducers) are electromechanical components in ultrasonic welding units. They have the task of transforming the high-frequency voltage provided by a generator into mechanical vibrations by use of piezoelectric effects.

By means of piezoceramic components, the converter converts the high-frequency electrical oscillation into a mechanical deflection of the same frequency. The output amplitude provided by the converter depends on the generator and the piezoelectric ceramics used. For a frequency of 20 kHz amplitude is usually close to about 10 µm (1 µm =1/1000 mm). This amplitude is passed into the booster.

1 The sections on the converter and the booster are taken from *Wikipedia* (www.wikipedia.de) (As of: 09.08.2008) – we wrote the *Wikipedia* article.

2.4.2 The booster (reinforcement or transformation component)

The **booster** in ultrasonic welding systems also has the function of changing the amplitude supplied by the converter and further guiding the sonotrode. Depending on the design of the booster, the amplitude can be reduced or increased.

In general, the amplitude is increased by the booster used in US welding because the plastics need larger amplitudes. The transmission ratio from the booster is usually between 1:1 and 1:3.

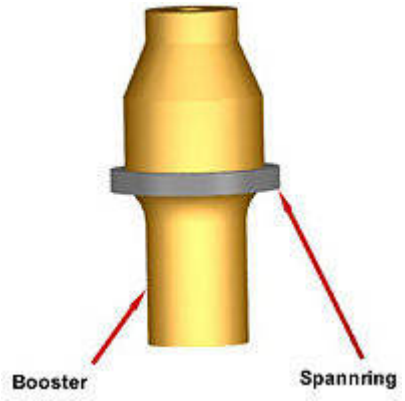


Figure 8 Booster with a transmission ratio of 1:1.5

In many systems the booster also functions to house the entire welding unit. Boosters are usually made of aluminum or titanium.

2.4.3 The sonotrode

The sonotrode is the ultrasonic welding tool and thus the link between the workpiece and the welding system. Only the sonotrode has direct contact with the workpiece.

There are a number of requirements to be considered in the design and construction of sonotrodes. Although they seem to be in order at first glance, improperly constructed or poorly finished sonotrodes may cause a cascade of problems. For example the measured frequency can be perfectly right and the sonotrode seem superficially fine when in fact the sonotrode is not oscillating properly and is therefore not in the required welding waveform.

2.4.3.1 Requirements for the sonotrode

Sonotrodes are highly complex tools. Below are listed the most important requirements that must be met by a sonotrode:

frequency	15, 20, 30, 35, 36, 40 and 70 kHz are used
resonance frequency	Not only must the sonotrode resonate in the correct frequency - this must be the resonance frequency
waveform	In most cases, a longitudinal waveform is needed. Transverse or torsional waveforms should be avoided
idle power	The idle power has an indirect bearing on the quality of the vibration and should be as low as possible
amplitude	depends on the material to be welded and the melting properties
amplitude distribution	should be as uniform as possible
geometry of the work surface	directly related to the geometry of the weldment
precision	especially relevant in 3D geometries and sensitive applications that require high precision manufacturing
transmission ratio	depends on the welding task and the melting behavior of the plastic
material	usually titanium, aluminum or various steels; voids or other structural damage must be excluded
quality of the work surface	e.g. coated, hardened, ground, etc.
the zero point position	sine waves must have a zone of minimal expansion - this is the “zero point" or the zero point position
stress distribution	stress peaks need to be avoided - at these points the sonotrodes tend to break

2.4.3.2 Examples of different types of sonotrodes

Below is a brief overview of different types of sonotrodes we manufacture:



Steel, 20 kHz



Titanium, 30 kHz
Mother – Daughter



Aluminium, 35 kHz, Rotor



Steel, 30 kHz



Steel, 30 kHz, Cutting Sonotrode



Steel, 20 kHz



Aluminium, 20 kHz



Titanium, 20 kHz



Titanium, 20 kHz

Figure 9 Examples of sonotrodes we manufacture

2.4.3.3 Special shape: the “Booster-Converter-Sonotrode”

In this special all welding unit the components are, due to specific technical requirements, integrated into a single component.

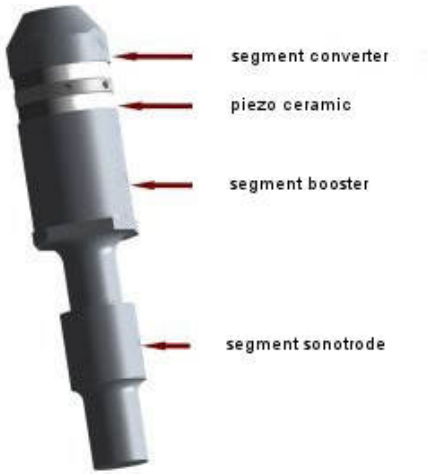


Figure 10 Special development converter - booster - sonotrode

3 The welding process

3.1 The main processes in ultrasonic welding

(Welding parameter highlighted with color)

Parts supply	Depending on the degree of automation welding parts are fed manually by the operator or automatically / semi-automatically
Working pressure	The working pressure (adjustable via air cylinder or motor) is determined based on the required performance, joint surface and part size
Lowering speed	Adjustable lowering speed of the feed unit
Welding time	Ultrasonic exposure time of the part to be welded
Hold time	Temporally variable force influence of the sonotrode on the joint zone during solidification of the melt
Trigger pressure	Ultrasound is raised only after exceeding a preselected trigger pressure (= pressure of the sonotrode on the welding portion)
Power supply	The preselected amount of energy to feed into the weldment before the ultrasonic process is stopped
Parts removal	Depending on the degree of automation welding parts are manually or automatically taken and passed to the welding machine

3.2 The four phases of plastic melting [2]

Melting of energy director	Energy director (see below) melts due to boundary friction and the beginning of plastification
Coupling of upper and lower parts	Further supply of energy by ultrasound produces further melting in the upper and lower parts, which are mixed together
Stationary meltdown phase	A melt of constant thickness is formed in the join and further supply of energy is no longer required
Holding phase	The workpiece is held in a precise position and cooled, wherein the sonotrode if necessary slightly stays behind

3.3 Types of welding

path-dependent	Welding paths are selected and the ultrasound is turned off after the end point is reached.
time-dependent	The welding process is switched off after a predetermined amount of time.
energy-dependent	A predetermined amount of energy is introduced into the part to be welded.

2 After *Potente,H.:* Fügen von Kunststoffen. Verlag Hanser (2004)

4 The energy director

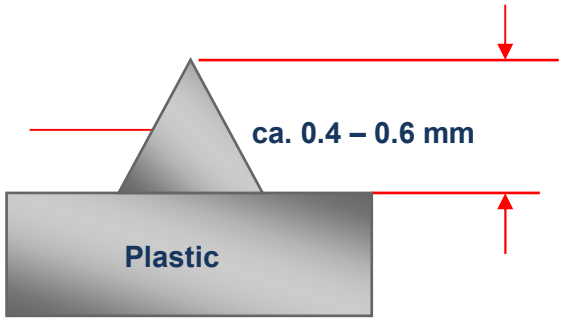


Figure 11 Construction scheme of energy director

When thermoplastic plastic parts must be ultrasonically welded together (e.g. in mobile phones and USB sticks), the joining zones are usually provided with energy directors .

Energy directors are about 0.4 – 0.6 mm high, circumferential, molded webs of material with a triangular cross section. The chosen angle at the top of the energy director is usually between 60 ° and 90 °[3].

With energy directors a targeted and focused energy input can be achieved. The frictional heat leads to an immediate melting of the energy director, which causes the surrounding material to start melting quickly as well. The lack of an energy director makes the plasticization of the material take longer, with additional contact pressure often required; the resulting weld is often poor.

In processes such as ultrasonic cutting or riveting or in the processing of films and fabrics, the lack of an energy director on the workpiece is compensated for by the geometry of the working surface of the sonotrode (for example, by knurling or riveting).

5 Failures in the ultrasonic welding process

In everyday practice there are always faults and errors in the welding process. It is important to recognize and fix them as soon as possible.

In the following we describe the most important errors and their correction.

3 All information refers to the most common values in practice, but these can vary quite considerably in individual cases. This note applies to many details in this guide.

Quick Overview of Errors and Troubleshooting in the US- Welding Process

Source of error	Error	Consequence	Reasons and corrective actions	
5.1 Sonotrode				
	5.1.1 Frequency			
		5.1.1.1 Generator overload		
			5.1.1.1.1 Component not correctly coupled	
			5.1.1.1.2 Broken thread in the sonotrode	
			5.1.1.1.3 Wrong frequency	
				5.1.1.1.3.1 Wrongly repaired sonotrode
				5.1.1.1.3.2 Wrong construction
		5.1.1.2 Generator gets off after operation		
		5.1.1.3 Sonotrode breaks after a short time		
		5.1.1.4 Sonotrode “screeches“		
			5.1.1.4.1 Incipient crack	
			5.1.1.4.2 Faulty connection of the components	
			5.1.1.4.3 Transmission ratio too high	
			5.1.1.4.4 Large anvil tolerance	
	5.1.2 Resonance Frequency			
	5.1.3 Waveform			
	5.1.4 Idle power			
	5.1.5 Amplitude			
	5.1.6 Amplitude distribution			
	5.1.7 Geometry of the work surface			
	5.1.8 Precision			
	5.1.9 Transmission ratio			
	5.1.10 Material			
	5.1.11 The „Zero Line“			
	5.1.12 Stress distribution			
	5.1.13 Temperature			
	5.1.14 Lifetime			
5.2 Booster				
5.3 Generator				
5.4 Converter				
5.5 Anvil				
	5.5.1 Wrong geometry			
	5.5.2 Poor alignment			
	5.5.3 Too low mass			
5.6 Coupling				

5.1 Faulty sonotrode

Sonotrodes must conform to a variety of requirements. Sonotrodes that do not meet these requirements, that were poorly designed or poorly manufactured, or that have been misused in the welding process are the most common source of errors that disturb the manufacturing process.[4]



You can touch a vibrating sonotrode with your bare hands only very gently and carefully. Even minimal pressure against the vibrating sonotrode immediately leads to painful injuries!

5.1.1 Frequency

The specific application determines what frequency to use. Therefore it is critical to properly select the plastics to be processed and the part size. Customers can choose from a variety of different generators with different available power levels in the frequency range of 15 - 70 kHz.

It is important that the entire welding unit (consisting of the converter, booster, and sonotrode) oscillate in the frequency provided by the generator.

Generators have a certain window, within which more frequency deviations can be “caught”. If the frequency of the sonotrode or of the oscillation unit, however, is too far outside this window, the generator is usually overloaded – it “gets off” (exits). Sometimes the window is very large, but usually it is about 0.5 - 1% of the specified nominal frequency of the generator.

More detailed information on the relevant frequency range or window can be provided by the manufacturer of the respective generator.

Evidence that could suggest that the sonotrode does not vibrate in the proper frequency includes:

4 Of course, a sonotrode can also break because of material fatigue and resulting cracking. This case will not be treated here.

5.1.1.1 Generator immediately goes into overload, possible reasons:

5.1.1.1.1 Component not correctly coupled

Actions:

- Unfasten components; check thread outputs and thread screws

- Clean the contact surfaces

- Tighten the components against each other **with the defined torque** (Take into account the manufacturer's information; as a rule of thumb: at 20 kHz – tighten the sonotrode component against the booster with a torque between 30 – 40 Nm; at 40 kHz – tighten the sonotrode component against the booster with a torque between 10 – 20 Nm.)

- Use special tools to screw the components together; use the special holes in the components for fastening the components

- Recommendation: First tighten the screw between the booster and converter firmly against the ground in the thread of the booster, then screw the booster against the converter; tighten the screw between the sonotrode and the booster firmly against the ground in the thread of the sonotrode first, and only then screw the booster against the sonotrode

5.1.1.1.2 Broken thread in the sonotrode (sometimes in the booster)

This error occurs fairly often, especially in aluminum sonotrodes. Even slight mishandling (such as one-sided load or improper torque of the sonotrode to the booster) can cause the thread to be damaged.

Actions:

Enlarge the thread by retrimming it to a greater number. In general, the resulting frequency change is not significant.

However, make absolutely sure that

- there is no "slot" in the immediate vicinity, such as for rectangle-grade sonotrodes with only one slot below the coupling thread installed. In such sonotrodes an enlargement of the thread can result in excessive material weakness.

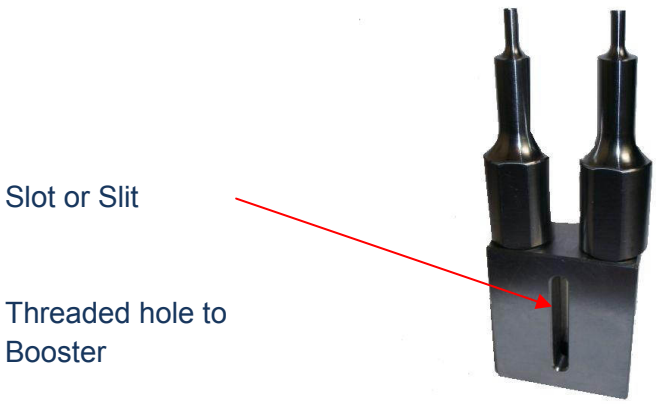


Figure 12 Mother – Daughter Sonotrode

- The thread is exactly centered (see also 5.1.8)
- Frequency measurement on the threading
- Think about the level (step) screw! The old thread should still be in the booster, so a screw with two different threads is required.

5.1.1.1.3 Wrong frequency

In idle generators frequency deviations of the sonotrode used are within certain limits. These generators get off only under load, because, for example, the sonotrode is warmed and the frequency thereby further “deteriorates". In such cases, is possible to measure the frequency of the sonotrode.

Causes of excessive frequency deviation include the following:

5.1.1.1.3.1 Wrongly repaired sonotrode

It is certainly possible to repair sonotrodes, but appropriate expertise and the necessary measuring equipment should be employed.

Moreover, it should be ensured that there is no associated change in the waveform (see 5.1.3) when a geometrical modification of the sonotrode is made.

5.1.1.1.3.2 Wrong construction

Only in the rarest of cases is corrective action possible to resolve wrong construction of a sonotrode. However, the potential for expensive consequential damage makes it inadvisable to continue work with a bad sonotrode. The sonotrode may wear out excessively fast, and it is even possible for the transducer (converter) to be damaged. Also, the quality of the weld is affected by a bad sonotrode.

If you suspect a faultily designed sonotrode you should contact the manufacturer or a neutral specialist. An FEM[5] analysis can depict the vibration behavior and identify the weaknesses[6].

5.1.1.2 Generator gets off after a certain period of operational time

Typical this behavior appears with sonotrodes whose frequency changes during use. Reasons for warming are also described in section 5.14.

Problem occasionally caused by:	- large sonotrodes, powered by - digital generators, constructed with a“narrow frequency band”.

Many digital operating generators “scan” themselves into a certain frequency. This is usually the resonant frequency, because the idle power, and thus the energy to be introduced to make the sonotrode vibrate, is at its lowest.

The sonotrode will usually be hot, as only its surface, which in relation to its volume is unfavorably small, can dissipate the generated heat. Also, if the sonotrode is not optimally constructed, it will have a high proportion of transverse vibrations, and the heat will build up more quickly.

This situation causes the frequency to fall as well. The generator still provides the original frequency, but the sonotrode begins to vibrate in another one. As the frequency falls further it eventually goes outside the window, and finally the generator “hangs” - it goes into overload, displays signs of trouble, or ceases operating.

There is a simple remedy: cool the sonotrode with compressed air.

---

5 FEM = Finite Element Method

6 However, you can find the most striking (and most common) problems for yourself with the Amplitude and Frequency Meter 9.3 AFM.

5.1.1.3 Sonotrode breaks after a short time

(although everything seems to be OK)

Under certain conditions a generator can meet a frequency which is a resonant frequency, but with too high a proportion of transverse / diagonal vibrations.

This happens most often when the ultrasonic process is nearing completion and all the important welding parameters such as the design of the plastic part and its location in the anvil have already been established.

Then it may be that an “optimal" design of the sonotrode is simply no longer possible and that too many compromises have to be made.

The generator “feels" only that the frequency is OK, so everything seems all right. This doesn’t prove, and it can’t be proven, that the waveform is the right one. The welding result will probably be bad, so in practice the welding pressure, welding time or both are often increased. Thus, the system continues to operate without warning, which can ultimately lead to rupture of the sonotrode.

Of course, it would be useful in such a case to improve the geometry of the parts and, if necessary, the situation in the housing. In practice, unfortunately, we can often only construct a new sonotrode and thereby avoid the dilemma of the wrong frequency.

A sonotrode can also quickly tear if the transmission ratio is too high (see 5.1.1.5).

5.1.1.4 Sonotrode “screeches”

5.1.1.4.1 Incipient crack

This implies, in most cases, an incipient crack in the sonotrode. If the sonotrode tears further, the generator will go into overload, because when the crack forms the frequency and the waveform change as well. (The frequencies are not in the ultrasonic range, but below, and will be heard.)

A crack in the sonotrode cannot be “repaired”. It is useful, however, to know the cause of the crack. Of course, it may be caused by material fatigue. However, a more accurate picture allows an analysis of the sonotrode geometry for possible vulnerabilities.

Optimizations which greatly extend the lifetime of a sonotrode are often possible.

5.1.1.4.2 Faulty connection of the components

A “screech" can also be heard when the individual components of the vibration unit are not connected properly or if the thread screw is loose or defective (see also 5.1.1.1.1).

5.1.1.4.3 Transmission ratio too high

A screech can sometimes be heard if the transmission ratios of the booster and sonotrode are too high.

5.1.1.4.4 Large anvil tolerances

Finally, an anvil with large tolerances or that enables large tolerances in the plastic part can be the reason for screeching during welding. Sometimes it's enough to compensate for tolerances in the anvil by e.g. glued fabric strips.

5.1.2 Resonance frequency

A sonotrode must resonate in the correct frequency, and this must also be the so-called **resonance frequency**. This means that a sonotrode can be moved with a small energy supply (excitation energy) from a natural oscillation which has the same frequency as the excitation frequency.

The classic example: Only a few people marching in lock-step may cause a stable bridge to swing in what is known as the resonance catastrophe. A variety of trucks could drive on the same bridge without anything happening.

If a sonotrode does not oscillate at a self-resonant frequency, it must be “forced" by the generator in the operating frequency. This increases the workload of the generator and the load of the entire system.

Whether the measured frequency of a sonotrode is actually its resonant or natural frequency can usually be inferred from the required idle power. If this is low - close to zero - you can assume that the measured frequency is the same as the resonance frequency.

The problem is that the resonance frequency of a sonotrode will not necessarily have the desired waveform (see also 5.1.3).

5.1.3 Waveform

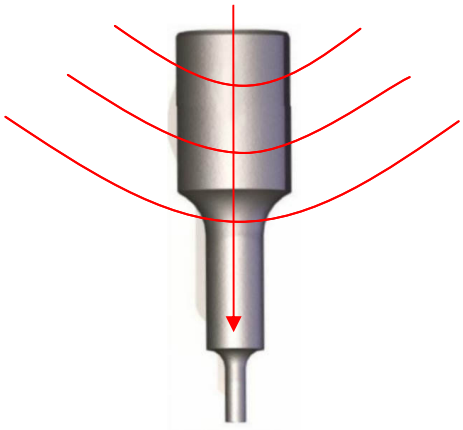


Figure 13 a ideal - typical sound waves running

In most applications the so-called longitudinal waves are needed since these sound waves meet at right angles to the workpiece, and thus have the best impact. Cross vibrations or transverse waves are undesirable[7]. They often necessitate increased welding times or a higher pressure of the sonotrode on the workpiece and thus shorten the life of sonotrodes and sometimes even of the converter.

A good longitudinal vibration ensures stable and uniform amplitude on the working surface of the sonotrode. Such amplitude shows a smooth sinusoidal curve on the oscilloscope.

If the proportion of transverse waves is too high, the process is not running optimally.

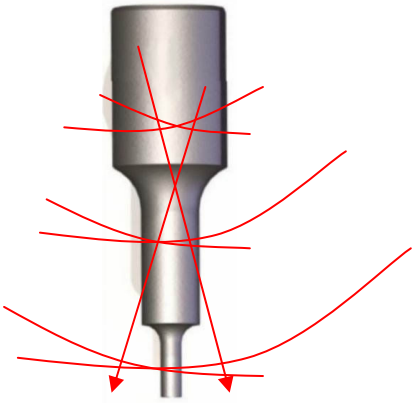


Figure 13 b Transverse waves running (schematic)

7 There are always transverse vibrations in sonotrodes, but there should not be too many.

With a laser vibrometer amplitudes can be measured and analyzed without contact. The method is very accurate. For operational practice, however, it is less suitable - the devices are very expensive and their handling is quite complicated.



Figure 14 The AFM 9.3 Amplitude and Frequency Meter

FEINTECHNIK R.Rittmeyer GmbH has developed the AFM 9.3 Amplitude and Frequency Meter specifically for industrial use. This device continuously measures the frequency of the vibrating sonotrode and can - indirectly - record the amplitudes and provide amplitude relations.



Figure 15 USM measuring head

The vibrating sonotrodes are “sampled” with the USM 3.1 measuring head (part of the AFM 9.3). The amplitudes of the longitudinal and transverse vibrations are registered and connected to each other depending on the position of the heads. The “amplitude ratio” allows conclusions to be made on the quality of the sonotrodes.

There is no such thing as “the” waveform of a sonotrode; ultrasonic vibrations are always put together from several oscillations that act to different degrees in different directions. The “waveform” is thus a resultant of all existing and overlapping vibrations. The direction in which the sonotrode has its strongest deflection depends on the selected design.

The sonotrodes in the examples below (Figures 16 & 17) all oscillate at the correct frequency (40 kHz in this case). In the example in Figure 16, however, the proportion of transverse vibrations is very high. This leads to a non-linear deflection.

In addition, the sonotrode is pressure-loaded (application: rivets). This and the faulty design will lead to premature rupture of the sonotrode.

The problem can be quite easily remedied by choosing a more appropriate geometry (Fig. 17). The geometric differences between the sonotrodes before and after optimization are sometimes hardly recognizable - the effects, however, are enormous.

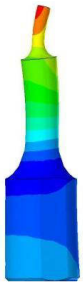


Figure 16 before optimization



Figure 17 after optimization

When designing a Sonotrode it is therefore important to make sure that the desired waveform is also the effective one. This is the real task of the developer and is achieved by choosing the “correct” sonotrode geometry.

5.1.4 Idle power

“Idle power” means the power input in watts which has to be provided by the generator to make a body oscillate in its self-resonant frequency. It should be as low as possible in sonotrodes (in contrast to other machine constructions in which it is usually essential to avoid resonant oscillations)[8].

The idle power indirectly says something about the quality of the vibration. In particular, a high proportion of transverse waves and cross vibrations requires additional servicing of the generator.

An increased idle power may be required in greater deviations from the predetermined frequency of the generator. In any case, a high power load is an additional load on the entire system.

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8 We try with our sonotrode constructions to stay below 5% of the performance of the generator. For a 2 kW generator this would be about 100 Watts.

Although this is an arbitrary value, it is very helpful as a guideline for assessing the sonotrode's quality. Most generators provide the idle power.

5.1.5 Amplitude

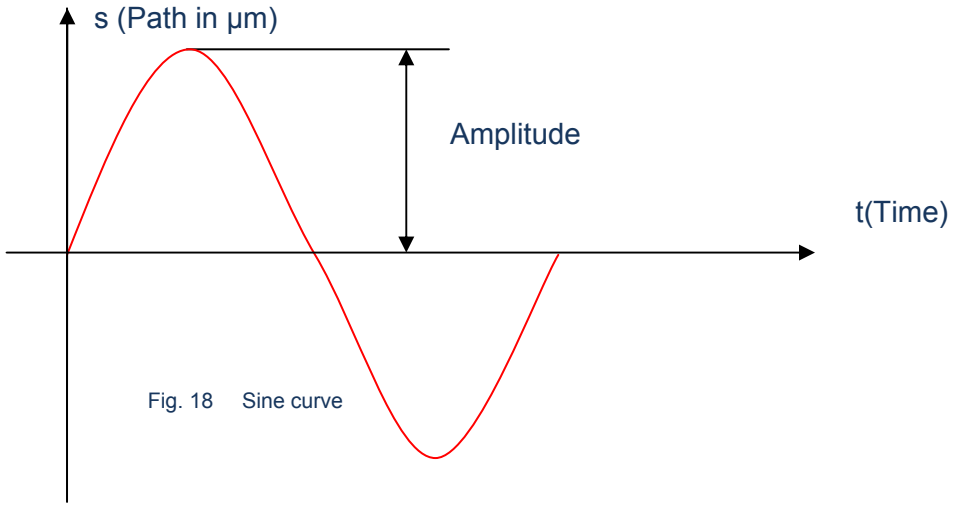


Fig. 18 Sine curve

The amplitude is the oscillation width of a sonotrode in its work area, and is expressed in µm (micrometers). The magnitude of the amplitude is affected by the output amplitude provided by the converter (transition piece), and the respective gain by the booster and the sonotrode itself.

Twice the amplitude, also the distance between maximum and minimum (in the case of symmetrical vibration), is sometimes referred to as peak-to-peak value.

The distinction is often not entirely clear – therefore, for safety's sake, make sure what exactly is meant: the “normal” amplitude or amplitude "peak:peak".

The required amplitude is determined by the melting behavior of the plastics used and other factors and can vary significantly. Amplitude must be taken into account in the design of the sonotrode (as well as the inclusion of the available booster).

The main adjustable parameters in ultrasonic welding are the welding time, the energy to be introduced and the pressure of the sonotrode (see also 3.1).

However if the sonotrode, for example, has insufficient available amplitude, the welding process will not succeed or will be insufficient.

If a sonotrode is badly constructed, the amplitude on the working surface may be different in different positions.

5.1.6 Amplitude distribution

It is difficult to “distribute” the amplitude evenly over the entire work surface. This task is particularly delicate in sonotrodes with different working levels, or even with introduced 3D geometries or for asymmetrical basic structures. Here amplitude variations are often immense, but may nevertheless be inevitable due to the geometry of the piece.

The object of construction is to select the design of the sonotrode in a way that the most uniform possible amplitude distribution is achieved. That’s why there are a number of design options available.

The amplitudes of the longitudinal and transverse vibrations on the outer flanks of a sonotrode can be recorded with the AFM 9.3.

5.1.7 Geometry of the work surface

This directly depends on the geometry of the welded parts or the desired result. Rivet sonotrodes, for example, are designed in such a way that, after their use, a “rivet head” is formed.

For the purposes of punching – as for buttonholes in belts – hardened steel sonotrodes are often used with a straight, polished work surface. Such sonotrodes are in contact with the punching tool and are subject to increased wear on the working surface.



Figure 19 Steel sonotrode for fabric processing

For the construction of sonotrodes it is very useful if there is some leeway in the choice of the particular external form. Unfortunately, not every structural dimension of a sonotrode leads to the best results. Basic square shapes, for example, rarely produce a viable vibration.

Therefore, it is advantageous if the sonotrode designer is taken on board as early as possible in the parts development process.

5.1.8 Precision

Especially 3D geometries and sensitive applications require high precision manufacturing.



Figure 20 Sonotrode with 3D geometry in the working surface

To a layman, sonotrodes may appear less complex than they actually are. They seem easy to produce and therefore easy to copy - a 1:1 replica seems so easy to make.

Besides the other problems with replicas, there are many sonotrodes whose tolerances are extremely tight, despite their apparent geometry. Even the slightest deviation can change their vibration behavior completely. The highest precision is required in the manufacture of such sonotrodes.

All angles in the axes should be exactly 90 ° .

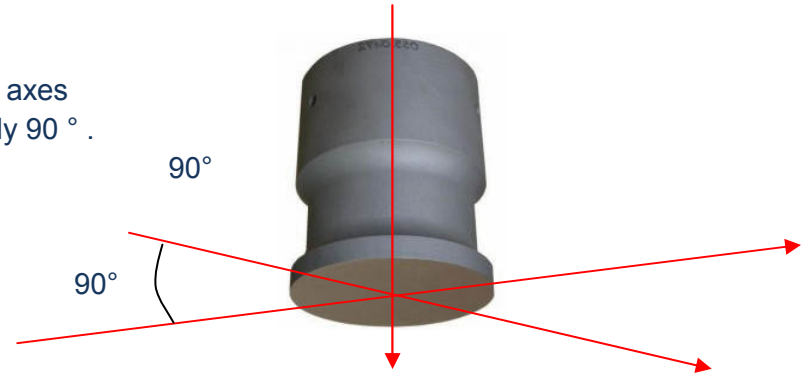


Figure 21 High precision in all axes

It is also important that the working surface be at an exactly 90° angle to the vertical axis of the sonotrode. This is the only way to ensure that the pressure is evenly distributed over the working surface of the sonotrode[9]. Unilateral pressure on the working surface must be avoided whenever possible.

5.1.9 Transmission ratio

The “transmission ratio” means the relationship of the input to the output amplitude.

Usually ultrasonic welding is done with amplitudes > 10 µm, since most thermoplastics require work amplitudes between 15 - 50 µm to get to an optimal melt. For the correct dimensioning of all welding components, it is always very important to have the required amplitude on the sonotrode. Negligence in this point usually has unpleasant consequences.

At 20kHz plants provide about 10 µm available output amplitude (Peak:Peak) to the generator. When using a booster with a transmission ratio or amplification factor of 1:1.5 and a converter output amplitude of 10 µm, the booster will give15 µm amplitude.

A sonotrode is usually also built with a transmission ratio, as evidenced by the narrowing of its cross-section at the work surface.



Fig. 22 Rectangle - stagger – sonotrodes with crosssection narrowing

If the selected transmission ratio of the sonotrode is also 1: 1.5, then the result at the work surface of the sonotrode is an amplitude of about 22.5 µm.

10 µm at the converter	x	booster transmission ratio	1.5	= 15.0 µm
15 µm at the booster	x	sonotrode transmission ratio	1.5	= 22.5 µm[10].

9 Of course, this only applies to sonotrodes that can be put on the welding parts with a straight work surface. With 3D geometries or inclined work surfaces uneven loads can often be largely offset by appropriate design measures.

10 With the amplitude and frequency meter, the input and output amplitudes can be measured, to store data and display the ratio of the stored values

You don't get the absolute value of the amplitude of a sonotrode from the AFM 9.3, but you can easily estimate it. You have to know only the output amplitude of the generator / converter (ask from the manufacturer) and the transmission ratio of the booster you're using (boosters are usually marked with a transmission ratio factor or a corresponding color).

For measurement with the AFM 9.3, this means that the amplitude value of the working surface of the sonotrode must be higher by about 1.5 than the amplitude value at the coupling surface of the sonotrode to the booster.

5.1.10 Material

Sonotrodes are made with special titanium, aluminum or steel alloys - all these materials are generally suitable and offer specific advantages. Some advantages and disadvantages are listed below:

Material Criteria	Titanium	Aluminum	Steel
Raw material costs	high	medium	low
Machinability	know-how required	light	medium
Basic hardness	low	low - medium	high
By hardening	not possible	not possible	untill ca. 64 HRC possible
Coating	possible	possible	possible
Construction size	very large possible	large possible	limited
Amplitude width	high	medium	low
possible transmission ratio	high	medium	low
Working surface regrinding	limited	limited	good
Continuous load	good	medium	medium

Your welding application requires an amplitude of 30 µm, and therefore appropriate transmission ratios – distributed as evenly as possible – must be provided in the booster and the sonotrode.

5.1.11 The “zero line”

Amplitudes, as the measured value of a sound wave, can be visualized, for example, with the USM 3.1 measuring head and an oscilloscope. They follow a sinusoidal curve shape.

Low or high points of the sine curve highlight the areas of greatest or smallest extension. The passage through the zero line highlights the corresponding zone without extension. For physical reasons, the geometric reduction level is set to increase the amplitude in this zone.

With the USM 3.1 measuring head connected to an oscilloscope, the sonotrode can “depart” and the amplitudes can be made visible: the input amplitude, the – usually larger – output amplitude, and the “zero – amplitude”.

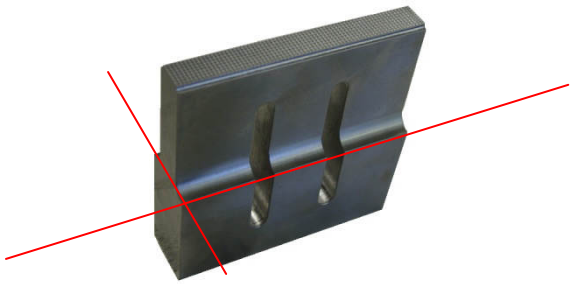


Fig. 23 Course of zero line

The absence of the zero line usually indicates a faulty design of the sonotrode.

5.1.12 Stress distribution

The geometric shape is determined in the design phase of a sonotrode. Although the frequency, amplitude values, transmission ratios, material, geometry, etc., might be in order, there may be unfavorable peaks in the material stress, zones of greater “stress formation”. Such zones are often found around the threaded hole or around the “slots”. They originate from poorly designed sonotrodes and can cause cracks.

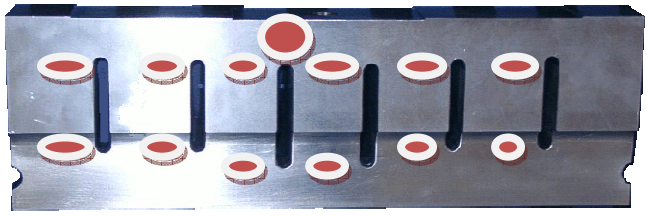


Figure 24 typical Stress zones

The design objective is to select the geometry of the sonotrode so that excessive stress peaks are avoided to prevent cracking of the sonotrode in these places.

5.1.13 Temperature

Sonotrodes may become warm or even hot.

The reasons for this are varied; it may be that

- the energy supplied was not completely converted into kinetic energy - for example, due to a high proportion of transverse vibrations - or

- the surface of the sonotrode is in an unfavorable ratio to the volume of the sonotrode, as is the case with large sonotrodes

Specifically, in continuous operation, large sonotrodes naturally warm up faster than small sonotrodes, with longer cooling phases between the welding operations.

The main problem with warming sonotrodes – besides the potential hazard to the operator from skin contact – is that the resonant frequency falls. This drop in frequency can be as large as several hundred Hertz, which can take the frequency outside of the “capture range” of the generator.

A typical indication of this phenomenon is when the generator always gets out after a certain period of operation.

A useful and simple-to-implement countermeasure is to install an air cooler. If this does not help, an analysis of the sonotrode and the amplitude distribution might be reasonable with a view to mounting a new design.

5.1.14 Lifetime

The “lifetime” of a sonotrode naturally depends on many factors. Below are mentioned:

- Material fatigue
- Material properties
- Design

It is possible to simulate the fatigue of a sonotrode in an adopted operating mode. The following can be considered as parameters: the hit frequencies, the material properties (taking into account molecular structure and expansion coefficient), the frequency of use etc. The so-called “Wöhler curve” can then provide information regarding how long the sonotrode may be expected to last under the assumed conditions.

However, the underlying mathematical algorithm is based on idealized conditions that are unrealistic in practice. It is simply impossible under normal production conditions to ensure consistently identical processing parameters. Therefore, such calculations are unfortunately only of limited use.

Nevertheless, you should definitely keep in mind the lifetime, because it is significantly impacted by the quality of the construction. Often, seemingly minor geometric improvements have enormous influence, as indicated in the example under 5.1.3 .

5.2 Faulty booster

Destruction of a booster in ultrasonic welding operations is quite rare. Boosters are usually built into the very stable geometry of a cylinder with a reduction grade and are very robust mechanically. Occasionally, however, the coupling screw of the sonotrode (rarely of the converter) gets loose. Then the thread may be damaged, often to the point of breaking the booster.

A faulty thread can be re-cut larger and thus repaired.

5.3 Faulty generator

Generators usually have an overload protection that protects the electronics if the product malfunctions, and are therefore rarely destroyed.

A fundamental problem, however, is if the frequency changes in the sonotrode during the welding process. This is for example the case when it becomes heated.

In such a case it may even happen that the waveform changes because of the change of frequency. A fault may then occur in the generator due to overload.

An indication of this is when a generator fault occurs only after a certain period of running time and after the sonotrode has warmed up. In such cases the sonotrode can be cooled by a constant air stream.

5.4 Faulty converter

It is more common for a converter to be destroyed[11]. This is particularly annoying because these components are very expensive. It is therefore important to make sure that incorrect use does not result in system destruction. The most common reason for damage to the converter is a badly oscillating sonotrode.

11 In general, only the piezoceramics in the converter are destroyed.

5.5 Faulty anvil

Even the anvil may be the reason for a poor welding result.

5.5.1 Wrong geometry or insufficient precision

Think about how delicate many welding jobs are. The energy director is often just 0.3 mm high, and the remaining welding path is hardly longer. One can thus imagine how hard it is to work with poorly positioned or poorly finished anvils. A few tenths of a millimeter inaccuracy can have a significant impact quickly.

5.5.2 Misalignment

Be sure to align the anvil correctly. Many manufacturers offer press benches that can be aligned. Apart from that, you should refer to the appropriate documentation to see how to use metal strips of different thickness to align the anvil exactly to the working plane of the sonotrode.

5.5.3 Inadequate mass

Another problem of anvils can be low mass.

In the upper part of the two parts to be joined the high frequency sound waves will be initiated by the sonotrode. This should liquefy the material in the joining zone by friction. However, this can work only if the sound waves are not transmitted through the lower part into the anvil. The anvil must therefore form a solid abutment. This is easiest to achieve with a large mass.

5.6 Faulty coupling

Remember to screw the parts together with the correct contact pressure, as mentioned in section 5.1.1.1.1.