WELD QUALITY EVALUATION IN RADIO-FREQUENCY PVC WELDING PROCESS

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Abstract: This article presents the technology and typical equipment for radio frequency welding of dielectric polar materials. This type of technology is used in production of PVC medical bags (drainage dialysis bags, peritoneal bags, solution bags, EVA bags etc.). The procedure is known and established in industry, but many different nonlinear process variables make the process complex and hard to tune. On the basis of the described experiment it is possible to conclude about the relationships between weld thickness, weld tensile strength and the energy input into the weld. Results show that weld thickness measurement could be used as a non-destructive method for evaluating weld strength.

Določanje kakovosti vara pri postopku radiofrekvenčnega varjenja PVC folij

Kjučne besede: Radiofrekvenčno varjenje, dielektrično segrevanje , spajanje PVC, polarizacija, varjenje PVC vrečk

Izvleček: V članku je predstavljena tehnologija in oprema za radiofrekvenčno varjenje dielektričnih materialov. Ta tehnologija se v veliki meri uporablja pri izdelavi medicinskih pripomočkov iz PVC-ja (dializne in raztopinske vrečke, drenažne vrečke, vrečke za umetno hrano ipd.). Postopek je sicer že uveljavljen in poznan, vendar je, zaradi velikega števila procesnih parametrov in nelinearnih povezav med njimi, precej kompleksen. Na podlagi interpretacije rezultatov izvedenega eksperimenta je možno sklepati o povezavi med debelino vara, natezno trdnostjo in vnosom energije na mestu vara. S tem se odpira možnost uporabe postopka merjenja debeline vara kot neporušno metodo za ocenjevanje kakovosti vara.

1. Introduction

Use of synthetic materials in industry has been increasing exponentially in the last few decades. An example of a product with high demand for quality and repeatability is a bag for peritoneal dialysis. Peritoneal dialysis bags are made of PVC sheets and PVC tubes which are joined with radio frequency dielectric welding procedure, known also as high frequency capacitive welding. The benefits of this process are short welding cycle, high energy efficiency and possibility to automate the production. Major drawback is that only nonconductive materials with a polar structure and reasonably high dielectric loss factor “$e_r \tan \delta$“ can be joined using this procedure.

The radio frequency welding procedure is present in different fields of industry. In automotive field Mitelea et al. /1/ were researching weld strengths of some dielectric materials with fabric insertion. Automotive sun-blinds are produced with radiofrequency welding procedure. Some statistical studies on weld strength of PVC with fabric insertion were made. The use of dielectric heating in food processing industry /2/ was researched by Zhao Y. et al. The use of radio frequency heating in wood processing industry for drying and gluing /3/ is described by Resnik J. Optional use of radio frequency process in future polymeric hermetic enclosures for in vivo environment /4/ was considered by Negin Amanat et al.

H.T. Sanchéz et al. developed SCADA system /5/ for radio frequency welding procedure of PVC bags for clinical use. Based on on-line sampling of voltage amplitude during welding cycle and statistic comparison to an ideal welding curve, potentially bad products could be eliminated in real time.

Some scientists conducted research on the electromagnetic field and temperature distribution in the specimen during welding. T. Leuca et al. presented the modelling of the electromagnetic field coupled with thermal field through radio frequency applicator /6/. C. Petrescu et al. used genetic algorithms to predict optimal parameters of radio frequency applicator with respect to uniform temperature distribution over the heated material /7/, electric and thermal distribution were modelled and calculated by 2D-FEM.

2. Theoretical background of electromagnetic dielectric heating

Electromagnetic dielectric heating is a volumetric heating method, since the heat is generated internally in the dielectric material. Temperature profile of heated material has a peak value in the centre of the material cross section. In a heating process, both dyes have lower temperature than the heated material itself. In case of a mass production the dyes have to be cooled in order to prevent arcing and maintain stability of the process, which is quite opposite to conventional methods of heating PVC films by introducing heat from heated plates.

Dielectric materials, as for example PVC, have polar molecule structure. One side of the molecule exhibits more positive charge and the other side exhibits more negative charge. Dipole moment, D, of such molecule, is proportional to a single charge (-Q or +Q) multiplied with their displacement r.

$$D = Qr \tag{1}$$

The distance between charges is related to chemical bonding and is considered to be constant. However molecules can rotate and vibrate. The amplitudes depend on the torque and surrounding local viscosity. Their motion tends to have a phase lag due to molecular friction and inertial effects.

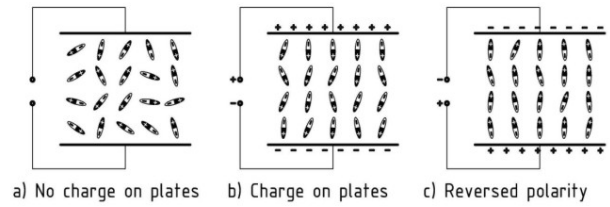

Fig. 1: Polarization of dipole molecules

Normally, when dielectric material isn't exposed to outer electric field, the molecules are randomly oriented throughout the volume, so the material is macroscopically electrically neutral (Figure 1, a). When dielectric material is exposed to electrical field, the dipole molecules tend to align along it (Figure 1, b and c). This process is known as dipole polarization. If the polarity of outer electric field is changing rapidly with time, the dipole molecules try to follow that by rotation. With each rotation some heat is generated due to intermolecular friction. The input power per unit volume, provided by the radio frequency welding machine, is proportional to the frequency and amplitude of the applied alternating electrical field, material permittivity and material loss factor eq. (2) /8/ .

$$P_{T,out} = E^2 2\pi n \varepsilon_r \varepsilon_0 \tan\delta \tag{2}$$

The RF welding process can be described with a model of a lossy capacitor (Figure 2), where the upper and lower dye are acting as capacitor plates and the heat is created in the dielectric material between them. Electrically it can be modelled as an ideal capacitor with resistor connected in parallel (Figure 2).

The admittance of such a circuit can be calculated as in eq. (3), where "A" stands for capacitor plates area and "d" stands for distance between the plates /9/.

$$Y = \frac{j\omega A \varepsilon_o \varepsilon_r^{'}(\omega)}{d} + \frac{\omega A \varepsilon_o \varepsilon_r^{''}(\omega)}{d} \tag{3}$$

The frequency ranges that are allowed in dielectric heating and welding applications are limited to one of the ISM[1] bands, defined by the ITU-R /10/ organization. In general all the devices operating in these bands must tolerate any interference generated by other ISM equipment. Most of radio frequency welding machines use 27.12 MHz, since it is the most tolerant band in ISM radio frequency spectrum.

1 *industrial, scientific and medical (ISM) radio bands*

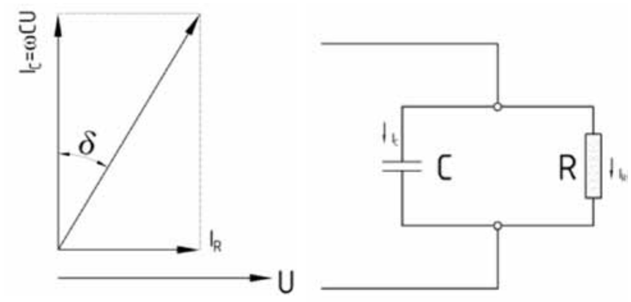

Fig. 2: U-I Vector diagram with equivalent electrical scheme

The power needed to heat up the dielectric material without considering losses at a contact area between dyes and material can be calculated as product of material density, volume, specific heat capacity and the time derivative of temperature eq. (4)

$$P_{T,in} = \frac{\rho V c \Delta T}{\Delta t} \tag{4}$$

Since the material in radio frequency welding applications is rather thin (in the range of millimetres) and the contact area is big, there are considerable heat losses from the heated material to the dyes.

In literature /8/ we can find some equations that successfully calculate power required to heat dielectric material while also taking into the account the heat losses. One of them is eq. (5), as follows

$$P_V = \frac{\pi^3 k \Delta T}{4d^2 f\left(\dfrac{\pi^2 kt}{c\rho d^2}\right)} \tag{5}$$

In eq. (5) "k" is the dielectric's thermal conductivity in W/m-°C, "ΔT" is the necessary dielectric temperature rise, "d" is the initial total thickness of the dielectric material while being pressed between the dyes, "t" is the heating time in seconds, "ρ" is the density of the dielectric in kg/m^3 and "c" is the specific heat of the dielectric in J/kg-°C.

Function "f" (eq. (6)) from denominator of eq. (5) is a third-degree polynomial

$$f(x) = 0.59 + 0.73x - 0.07x^2 - 0.29x^3 \tag{6}$$

where variable "x" is defined as:

$$x = \log_{10}\left(\frac{\pi^2 kt}{cpd^2}\right) \tag{7}$$

The expression in eq. (5) is valid when the value of "x" in eq. (7) is within the range of $0.1 \le x \le 10$.

3. RF Welding machine and identification of process variables

The typical RF welding machine consists of a high frequency generator (Figure 3, D) and an impedance matching capacitor which regulates the electrical power transmission to the load. The load is basically capacitor with PVC foil as dielectric material and tool acting as bottom/top capacitor plates. As a rule of thumb, the power needed to join two PVC foils with a thickness of 0.5 mm is about 25 W/ cm^2 /11/, for thinner foils the power increases exponentially due to higher heat transfer to dyes.

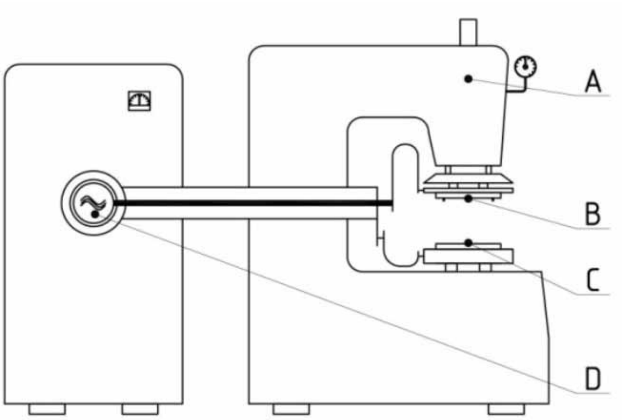

Fig. 3: Typical RF welding machine

The upper and lower dye (Figure 3, B and C) play three roles:

1) Provide high frequency electrical energy to the material
2) Enable fusion of the melted material due to the applied mechanical pressure
3) Determine the size and the shape of the weld

The dyes (in literature also referred as "electrode" or simply "tool") are usually made of highly conductive and easy to machine materials, such as copper or brass. Uniform height, rigid construction and parallel mounting on the machine are crucial for high quality welds.

The press (Figure 3, A) provides pressure in the material during heating in order to avoid or minimize the possibility for material deconsolidation /12/.

Radio frequency dielectric heating is a dynamic process. During the welding cycle temperature of dielectric material is rising, at the same time distance between upper and lower dye is decreasing due to lower material viscosity. With smaller distance between the dyes, electric power absorption in the load is changing, eq. (2), as well as heat absorption in the load, eq. (5). On top of that, material loss angle and material permittivity exhibit positive nonlinear trend with temperature rise. As a consequence dielectric medium absorbs more energy (eq. (2)). This effect is also known as "thermal runaway" /13/.

To control all the welding parameters, modern radio frequency welding machines have a control system that is able to tune the power transferred to the load by changing the capacitance of the variable capacitor. It is also possible (for the operator) to adjust following process variables on the control panel:

- Dye clamping force (usually it is a pneumatic or hydraulic system)
- Spacers for limiting minimum distance between the dyes
- Anode current starting value (starting position of variable capacitor plate)[2]
- Final anode current during welding (function of variable capacitor capacitance)
- Velocity of variable capacitor plates during tuning2
- Pre welding time2
- Welding time
- Cooling time after welding

Upper electrode defines welding shape by its construction, as can be seen in Figure 4. Lower dye can be flat or with opposite contour. Use of buffer material prevents arcing and minimizes heat loses from dielectric material to the lower dye. In cases when besides welding also cutting with radio frequency is applied, the use of buffer material is essential. Buffer material must have high dielectric strength and low dielectric loss factor.

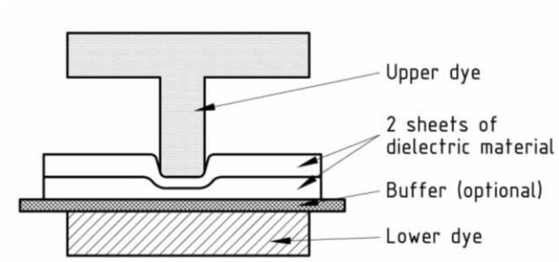

Fig. 4: Section thru welding configuration

Time diagram of a typical welding cycle in a single phase radio frequency welding procedure with automatic power tuning is shown in Figure 5. Process consists of three successive phases:

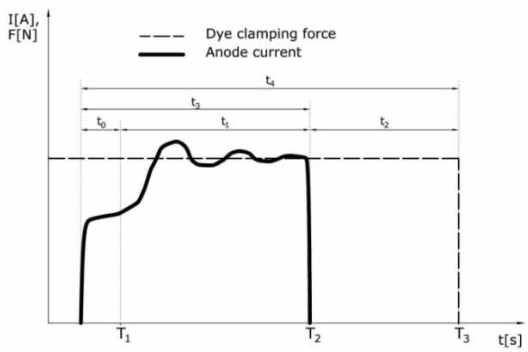

Fig. 5: Welding sequence

2 *Only machines with automatic tuning control system*

Phase 1:	Initialisation phase: the press closes, radio frequency source is switched on and a variable capacitor is set on a pre-welding value. Control system controls only variable capacitor's plate position. Dielectric material between the dyes is under full compressive load and it begins to heat-up with low intensity. This phase can be seen in Figure 5, between T_0 and T_1.
Phase 2:	Heating phase: after initial delay (t_0, Figure 5), control system is switched from a capacitor plate position control to an anode current control. Intensity of heating rises till the anode current set point is reached. Temperature of material rises above glass transition, material changes from solid domain to flow domain. Distance between the upper and lower dye is decreasing due to excess material flow. On Figure 5 this phase can be identified as area between T_1 and T_2
Phase 3	Consolidation phase: The radiofrequency heating source is switched off, the press remains closed, material temperature begins to fall. Weld shape is formed with a material changeover from flow domain into a solid domain. After pre-determined delay the press opens and the welding procedure is finished.

Energy input (in arbitrary units) from a radio-frequency source to the material is defined by area under the anode current curve (with the assumption of constant voltage). It can be calculated as an integral of the anode current over time (eq. (8)).

$$P_{in,arb} = \int_{T_0}^{T_2} I_a(t)\,dt \tag{8}$$

4. Experimental investigation of the relationship between weld section thickness and weld strength

The optimal set of parameters for radio frequency welding process is hard to obtain and maintain during the production. Environmental conditions, such as humidity and temperature together with material thickness and electrical characteristics non-uniformity, can have big influence on weld quality. Due to many variables, the radio frequency welding procedure can be categorised as a complex process. There is a lack of simple, efficient and generalised model to predict and evaluate the optimal set of parameters.

In order to evaluate the repeatability of welding process and to perform sensitivity test of some parameters, an experiment has been performed, using a RF sealing machines for PVC solution bags production. Altogether 400 samples were welded with 5 sets of welding parameters. The experiment took place in a clean room environment with controlled ambient temperature and humidity. The first set of samples was welded as a reference, so the standard production parameters were used. In other 4 samples sets anode current value, as well as welding time were varied.

The test welding tool consists of two dyes in line, so with each welding cycle we got 4 samples marked "A1", "A2", "B1" and "B2" (Figure 6).

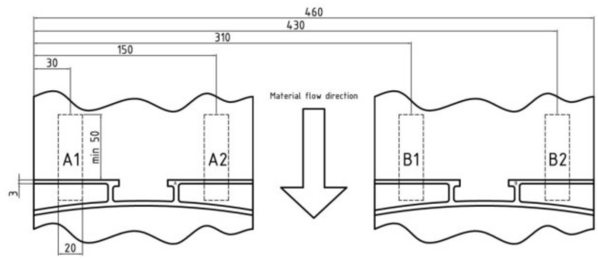

Fig. 6: Location of the samples on RF welding machine (top view – two independent PVC films in tubular form, which run under two separated dyes mounted on a tool plate)

The process parameters which were changed in the experiment are listed in Table 1. For each set of the samples only one parameter was changed at a time, others remained fixed and equal to standard welding parameters.

Table 1: Parameter values for sample sets

Welding parameters	**Flat welding time /s/**	**Power adjustment potentiometer /1...10/**
Standard production parameters	2	5
Increased power	2	8
Decreased power	2	2
longer welding time	3	5
Shorter welding time	1	5

Actual anode current profile for each welding cycle in the experiment was recorded with a digital oscilloscope and input energy (arbitrary units) for each welding cycle was calculated from the eq. (8). Input energy (arbitrary units) and anode current curves (arbitrary units) comparison for all five parameter sets used in the experiment can be seen in Figure 7. Average input energy in arbitrary units for each set of experiment is listed in Table 2.

Typical process control tests performed in production, with which the welding process is evaluated, are non-destructive, such as dimensional and optical inspection of the product integrity (all welds present, welds well defined, tactile feeling of the welds), weld thickness, peel test and leakage test. It would be time consuming to perform destructive tensile tests on regular basis although standard manual peel test gives good feeling about weld force.

That is why one of the main goals of this experiment was to find out if there is any connection between tensile breaking force needed to break the specimens apart and welding set-up.

In the experiment, thickness of a weld zone was measured in the middle of a weld for every sample after the radio frequency welding procedure. Locations were marked as "A1", "A2", "B1" and "B2" – see Figure 6.

For each set of samples the average thickness for a particular group of samples was calculated. The results are

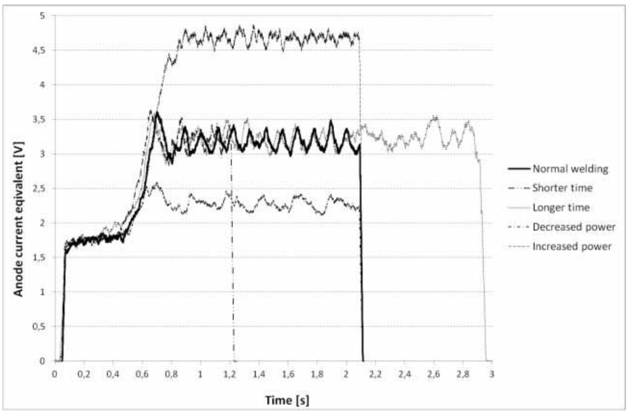

Fig. 7: Time series of anode current amplitude (measured as a voltage drop on a resistor) recorded with DSO

shown in a column chart (Figure 11). Initial total thickness of the material was 0.7 mm - two sheets, 0.35 mm each.

After the weld thickness measurement samples were precisely cut on 20 mm bands, according to Figure 6, the same samples were clamped into a tensile strength testing machine, as shown in Figure 9, and records of maximum destruction tensile force for each sample were taken. Again, the average values for each of the sample groups in each set of experiment, were calculated. The results are presented in Figure 10.

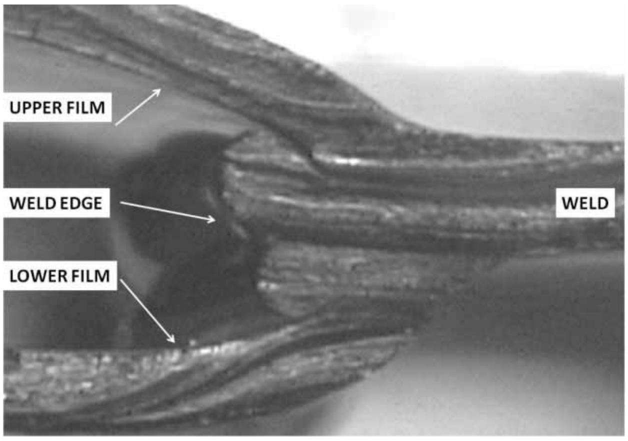

Fig. 8: Magnified picture of a weld cross section; weld edge with extruded material is clearly seen

5. Interpretation of results

Generally, weld thickness decreases with longer welding time and higher input power. Dependence of weld thickness on power is more pronounced, as expected.

Tensile strength dependence on welding time and power is not so obvious. However, using short welding times and lower power do not produce satisfactory results.

This means that for a good weld input power threshold must be exceeded. This is demonstrated by observing

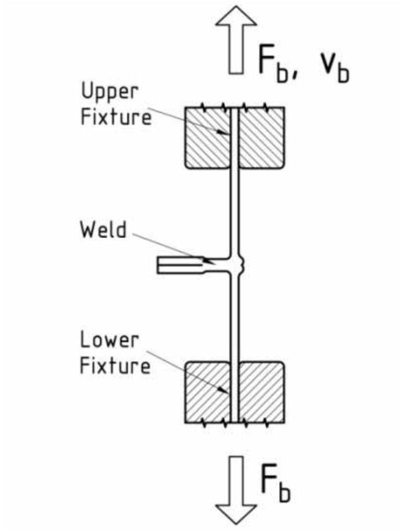

Fig. 9: Sketch of a tensile test Fb=pull force; vb=pull speed(10mm/min)

sample B2 which was not welded well applying minimum power (thickness equal to original thickness, tensile force practically equals to zero). For this particular case power set to value "2" is right below allowable power threshold.

In practice this means that by obtaining weld thickness in the range of 45 – 65% of total material thickness should guarantee its high tensile strength. Thicknesses above 80% of the original film thickness usually mean low weld peel force while thicknesses below 40% of the original film thickness usually cause sharp welding edges that can be easily broken.

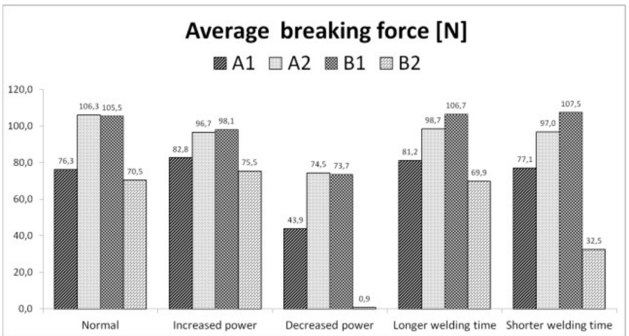

Fig. 10: Average tensile breaking force of the samples

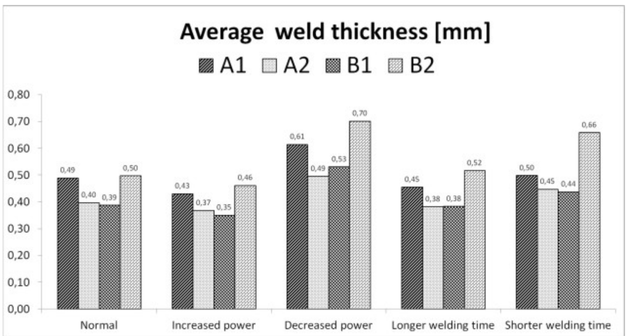

Fig. 11: Average weld thickness of the samples

In further analysis only sample groups "A2" and "B1" were taken into account. Since only center of the tool was clamped by pneumatic valve, tool edges exhibited deformation which resulted in higher distance between top and bottom dye. This is why samples of groups "A1" and "B2" show exceeded nonuniformity and were intentionally omitted.

Input energy, calculated by eq. 8, depends mainly on two machine parameters: welding time and anode current setpoint. In order to fix as many variables as possible, only the samples with the same welding pre-set time were considered. Samples obtained by welding sets with "decreased power", "normal welding parameters" and "increased power" share the same pre-set welding time, so they could be compared together.

It is expected that the weld strength is a function of input energy with a global maximum somewhere over the range of input energy, under assumption that minimal power needed to start melting of material is exceeded. The similar assumption should be valid for weld thickness, which should decrease with increasing input energy.

These assumptions are confirmed observing graphical representation of breaking force versus input energy (arbitrary units) and graphical representation of weld thickness versus input energy (Figure 12). Nonlinear dependence between those variables exists. In Figure 12 lines represent polynomial fit to the data.

Without a doubt this experiment should be performed with more intermediate power set points to obtain more data and allow more accurate interpretation of results

Table 2: Average arbitrary input energy for each set of experiment

	Average input energy (arbitrary units)	Standard deviation of input energy
Shorter welding time	3,0	0,04
Decreased power	4,5	0,03
Normal welding parameters	5,8	0,05
Increased power	7,9	0,09
Longer welding time	8,6	0,06

6. Conclusion

It can be seen (Figure 10 and Figure 11) that there is a relationship between weld thickness and tensile breaking force. In nearly all cases the maximum breaking force is achieved on samples with thicknesses of about 45% to 65% of initial material thickness. As expected, break force begins to decrease with decreasing weld thickness since weld edge effects, and not the weld body itself, start to define its strength.

This result is very encouraging and gives some benefit to production process control. Only by obtaining weld thicknesses in the range of 45 – 65% should guarantee high weld tensile strength. Thicknesses above 80% of the original film thickness usually mean low weld peel force while thicknesses below 40% of the original film thickness usually cause sharp welding edges that can be easily broken.

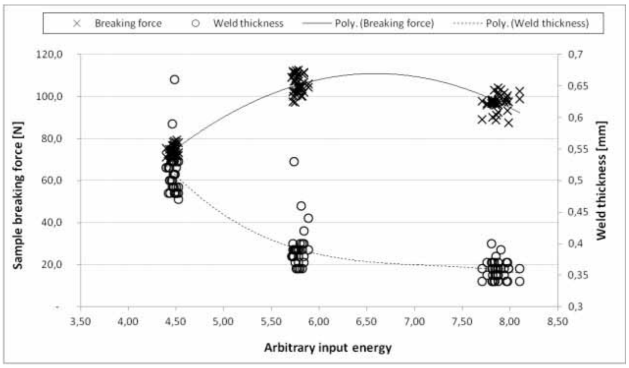

Fig. 12: Data point distribution of breaking force and weld thickness with respect to arbitrary heating energy for samples A2 and B1. Lines represent polynomial fit to the data

We should also comment that if welding power below threshold power is applied (some of samples A1 and B2) we observe larger nonuniformities in weld thickness and break force. Again, if production control finds samples with large thickness nonuniformities and low manual peel force, it should trigger alarm and technicians should start looking for its cause.

We will focus future experiments in obtaining more data to confirm conclusions presented in this article with higher reliability.

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