Proactive control of weld dimensions in robotised MAG welding

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Abstract

Keeping all welding dimension on target and within specification limits is a multi-parameter optimisation problem that involves trade-offs between potentially contradicting requirements. In the fillet weld case study, the balancing act is to keep fillet weld bead thickness on target and simultaneously fulfil a minimum requirement of both weld toe radii and weld penetration of the base material. With a robust engineering approach, consisting of screening, modelling, multi-parameter optimisation and robust assessment, some interesting observations regarding the relationships between welding control parameters and resulting weld dimensions have been made. The parameters that directly influence welding productivity, such as beam power (U, I), speed and material feed, were found to be of secondary importance for controlling the toe radius, penetration dimensions and the weld bead thickness, compared to the influence of the welding geometry (torch and plate positions). With the multi-parameter model developed, it was possible to predict and verify a setting of the welding geometry that fulfilled all weld dimension specifications simultaneously and to estimate the width of a production window that allows for some control factor variability. This result opens up a new strategy to the development of both welding productivity and quality at the same time, even though it takes some off-line response surface modelling (RSM) or on-line evolutionary process (EVOP) experimental procedures, at least for this particular welding scenario: a 5mm fillet welds with at least 2mm penetration and smooth (>1mm) weld toe transition.

Introduction

A fillet weld is a standard shape of joints between two plates, widely used in industry. It is illustrated in Figure 1 with two of the design parameters: ‘a’ – weld bead thickness and ‘i’ – weld penetration at the interface between the plates (1). Static and dynamic dimensional requirements on these joints also classify the weld toe radius at the transition between the plates and the weld bead (flange, f. and waist, w.) for different fatigue life requirements.

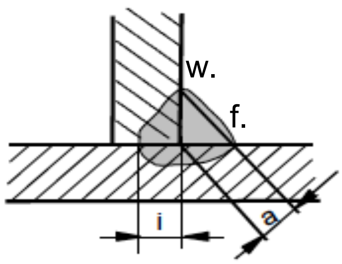

Figure 1: Fillet weld with design dimensions 'a' thickness and 'i' penetration. Toe radii at waist plate (w) and at flange (f.) are also located.

The process studied here is an industrial robotized MAG welding process located in the frame manufacturing process at the Volvo Construction Equipment wheel loader plant in Arvika, Sweden. The investigation is a small part of the long-term goal to understand how to design fatigue loaded welded joints in heavy-duty vehicles financed by FFI[1]. The initiation and preliminary results of this work was reported at the Swedish Conference on Light Weight Optimized Welded Structures, March 24-25, 2010, Borlänge, Sweden [8]. Here the modelling part is reworked with the intention to make it more useful in daily operation at the plant using a standardised and documented modelling procedure and a commercially available software package described below.

The total modelling procedure consists of the following stages: planning, screening, modelling, response-optimization, sensitivity-analysis and process-window-consideration. The modelling step was also preceded by measurement system analysis and parameter screening described in [8] and subsequent work [9-12]. The screening consisted of both qualitative and quantitative steps. Process engineers and technicians participated in process mapping (using p-map tool) that resulted in a gross list of 24 relevant control parameters (x_i). By the subsequent qualitative cause and effect analysis (using cause and effective matrix tool) the process specialists selected 11 parameters with known and suspected impact on the variation of the process output responses (y_j) of weld bead dimensions, to be improved, defined above: throat thickness, a [mm], penetration, i [mm] and toe radiuses, t [mm]. The influence of these 11 parameters was ranked with a quantitative screening using a saturated fractional two-level factors design experiment with 16 runs. The thirteen parameters excluded were considered of less importance for the quality characteristics studied and set to their most relevant settings.

The screening experiments separated further 6 parameters with limited influence relative to the 5 most influential ones. The result from the screening was rather surprising to the process specialists; all parameters controlling weld process productivity could be separated from the parameters controlling weld bead geometry and fixed to their most favourable setting aiming at as high productivity as possible within the recommended settings for the target bead thickness (a = 5 mm) specified. The productivity parameters (beam power, speed and wire feed, oscillation width and oscillation frequency) were of significant lower importance for the bead dimensions than the welding geometry parameters (torch (gun) angle across bead, slit between plates, weld position (waist plate angle), up-/down hill welding, pushing or pulling beam) within the range of the parameters tested. Figure 2 describes the resulting modelling scenario after screening with a p-diagram.

The result from the screening was interesting. Most welding modelling in the literature mainly concerns the influence of arc parameters at some fixed welding geometry, for example [2], where no screening was reported and the parameters included for weld bead geometry modelling contains both geometry and productivity variables; such as: welding speed [cm/m], arc voltage [V], wire feed rate [m/min], torch angle (°), nozzle/plate distance [mm]. Baghel [13] reviewed quite a lot of papers discussing the influence of welding productivity parameters on bead geometry, but only a few of them have included a wider range of welding geometry parameters in their studies, apart from nozzle/plate distance and torch angle.

[1] FFI - Strategic Vehicle Research and Innovation. Currently there are five collaboration programs: Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology, http://www.vinnova.se/en/FFI---Strategic-Vehicle-Research-and-Innovation/

There is no doubt that the productivity parameters are important for the final bead geometry. But if they are of less impact than the welding geometry parameter, as our screening experiments indicate (Figure 2), an exciting question arises:

- Can the welding geometry parameters be used to compensate for bead geometry losses when productivity in the process is tuned up?

In order to explore this research question, the first issue would be to establish a robust process window where all weld geometry specifications are fulfilled simultaneously at the present production rate. That is, to establish a stable or predictable baseline for the welding directly and to explore a potential methodology for multi-parameter process stabilisation indirectly. Welding optimisation is a complex issue containing contradictory objectives and noise (from input, process and measurement systems) in the same range as the response variation from control parameter changes themselves, in which case one-factor-at-a-time approaches become insufficient.

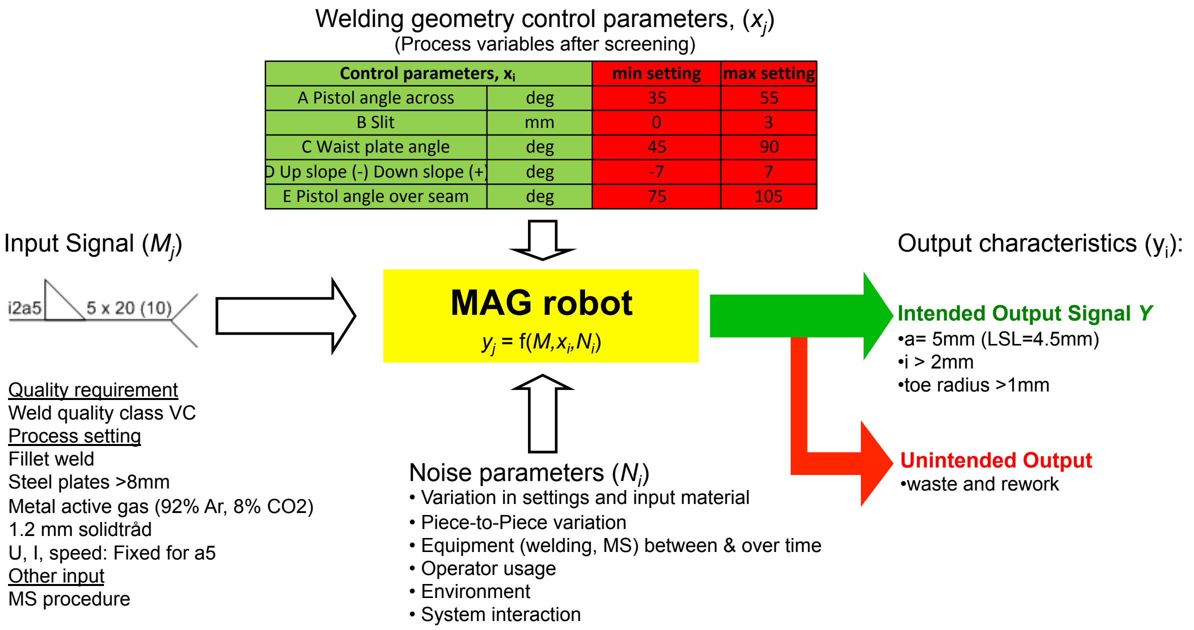

Figure 2: A summary of the modelling scenario after screening. The p-diagram show robotised MAG welding. Input signal (M_j) represents the fixed setting after screening. The welding geometry control parameters (x_i) are open for optimization within the ranges listed. The modelling aim is to fulfil the specification on the output characteristics (y_j). The noise parameters (N_j) are only listed as categories from which scatter are to be expected.

Modelling

Design of experiment (DoE), response surface modelling (RSM) and evolutionary operation (EVOP) for manufacturing process development are considered well-established techniques for multi-parameter optimization problems within Quality and Six Sigma Engineering. Many textbooks are written on the topic; such as the first (1978) and the second (2005) editions of the classic textbook: 'Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building' by George Box, William Hunter and Stuart Hunter [3] and many other excellent adjacent references within the field; such as: Donald J. Wheelers 'Making sense of data' from 2003. Also several pocket handbooks are available; such as: The Lean Six Sigma

Pocket Toolbook: A Quick Reference Guide to 100 Tools for Improving Quality and Speed, by George, M. L., et al. [4].

The re-modelling of the data from [8] in this work follows the 'Visual Six Sigma Roadmap' from the textbook 'Visual Six Sigma – making data analysis lean' [6] using the JMP® 10 software package from SAS [7]. The roadmap below starts with analysis of historical process data. We have used it as is to assess the experimental data collected earlier:

- Uncover relationships
  - Dynamically visualize the variables one at a time
  - Dynamically visualize the variables two at a time
  - Dynamically visualize the variables more than two at a time
  - Visually determine the hot Xs that affect variation in the Ys
- Model relationships
  - For each Y, identify the hot Xs to include in the signal function
  - Model Y as a function of the hot Xs; check the noise function
  - If needed, revise the model
  - If needed, return to the Collect Data step and use DoE
- Revise knowledge
  - Identify the best hot X settings
  - Visualize the effect on the Ys should these hot X settings vary
  - Verify improvement using a pilot study or confirmation trials

Uncover relationships

The data collected in the modelling step after screening was collected in a series of experimental blocks (Occ.) progressively building a full factorial experimental design (2^5) with central and axial points (facial) shown in Appendix A [8]. There are 50 runs in total.

Experimental range

The first consideration was to investigate if the experimental range for the control parameters allowed that the bead specifications could be fulfilled simultaneously. In Figure 3, the distributions of the weld bead dimensions (y_j) are shown for all 50 runs above and welding geometry (x_i) below. The darker selection highlights those runs that simultaneously fulfil all requirements – mainly centred in the experimental range for all control parameters; indicating a symmetric selection of experimental factor levels. Based on this graph, it is possible to conclude that the ranges are wider than potential process windows and that modelling should be carried out in order to find a recommended setting and acceptable process window width, taking variation along the welds into account. The variations along the welds have been considered. For the selected runs, the worst readings of the weld quality are above the lower specification limit (LSL). This is indicated by the dark green (shaded) areas of the histograms in Figure 2.

On the other hand, if only one of the requirements is to be fulfilled, for example, a > 4,5 mm. 35 out of the 50 of the different settings can fulfil this (see Figure 4); some however with the risk to fail on either toe radius on the flange (tf) or on one of the penetrations[2] (iw or if). Choosing any other of the requirements shows the same pattern; it is easy to fulfil one requirement, but there is a risk to choose settings that fail on any or several of the other requirements. This makes a one-factor-at-a-time approach unpractical and tedious, particularly in such a case, since there is so much noise.

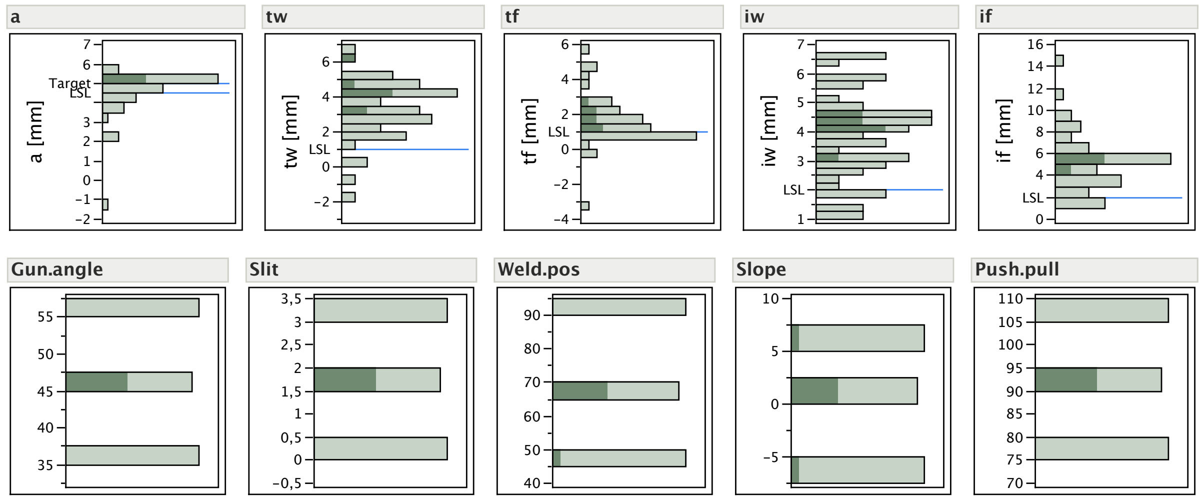

Figure 3: Distributions of the weld bead dimension for all 50 runs, above. The dark green selection is the 8 runs that simultaneously fulfil the requirements on all responses. Variation along the weld is considered, that is the dark green has y_{mean} – 0,5 y_{range} > LSL (lower specification limit). Below are the settings for the non-scrap producing 8 runs, mainly centred in the experimental range.

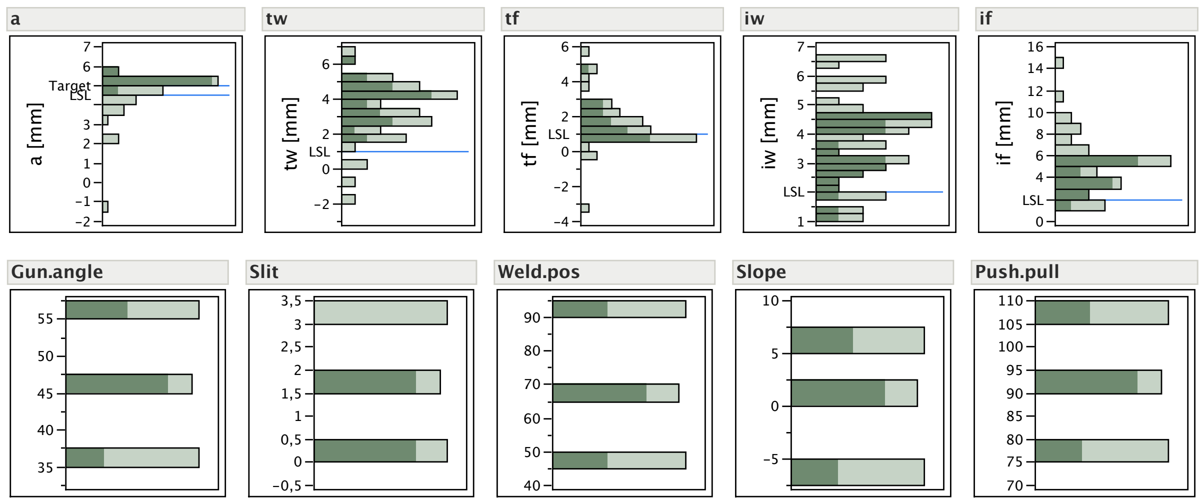

Figure 4: When selecting runs that fulfil only one-at-time of the requirements. For example: 'a' > 4,5 mm, there is a wide range of settings that can be used (below), 35 runs fulfil the requirement on 'a', but some risk to fail on either toe radius on the flange (tf) or one of the penetrations measures (iw or if)[2] (above); the dark selection below the LSL.

Modelling region and Outliers

The next step is to check if all combinations of factor levels produce welds that could be considered acceptable and be used as modelling data. Figure 3 and Figure 4

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[2] Penetration is measured both above and below the slit, iw and if, since the slit between the plates can be up to 3mm, which allows a skewed penetration front.

show evidence of potential outliers in the data, where the welds significantly deviate from the specification, that is, scrap. Stratification on the control factors (x) revealed that all outliers come from the same combination of welding geometry: a 3,0mm slit between the plates and the Gun.angel at 55° (Figure 5). It is when the arc is blowing into a wide slit, pushing most of the welding material into it resulting in 'a' out of spec., and no control of the toe radiuses – large variation (Figure 6).

Since the combination of high Gun.angle and wide gap is producing scrap; it is an unwanted combination and therefore not used for production whatsoever. In order not to lose model accuracy in the area of interest by over-fitting the model to these outliers, it was decided to exclude them from the data set before modelling. In other words, the model will not be valid for this control parameter combination. The aim is after all not to produce scrap. This step of the analysis was overlooked in the preliminary modelling done in [8] resulting in over-fitted unrealistic models.

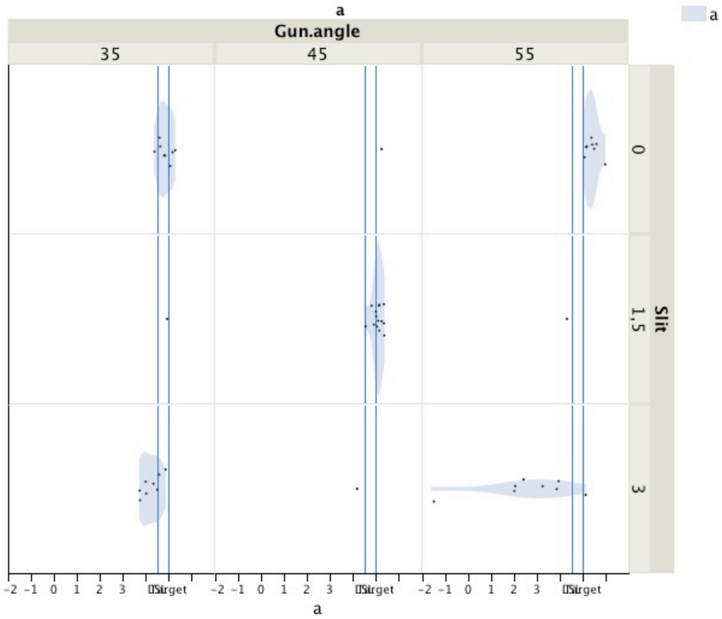


Figure 5: Stratification on Gun.angle (angle of torch from the waist plate) and Slit (gap between the plates) reveals that there is a significant larger variation in 'a' at the combination of Gun.angle at 55° and 3 mm slit between the plates (lower right corner).

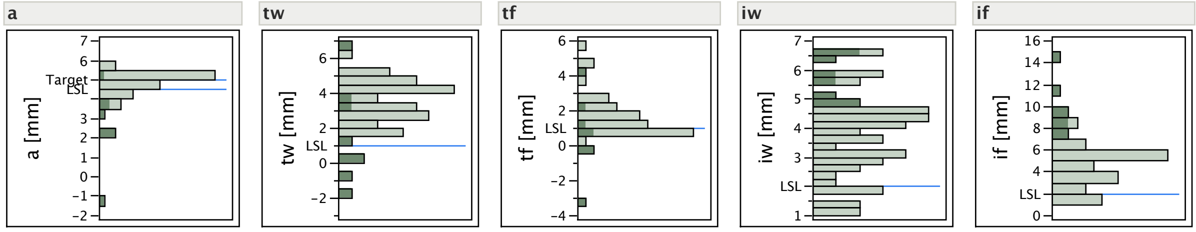
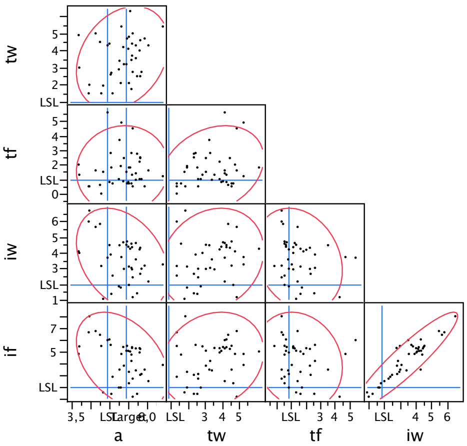


Figure 6: Selection of runs producing scrap comes from the same combination of welding geometry: a slit of 3 mm between the plates and the Gun.angle at 55°; that is, when the torch is blowing almost strait into a wide gap. It pushes the welding material into the gap and is out of specification. Penetration as a natural consequence is larger, but there is no control of the toe radius; the variation is large both on the toe radius at the waist, tw, and at the flange, tf.

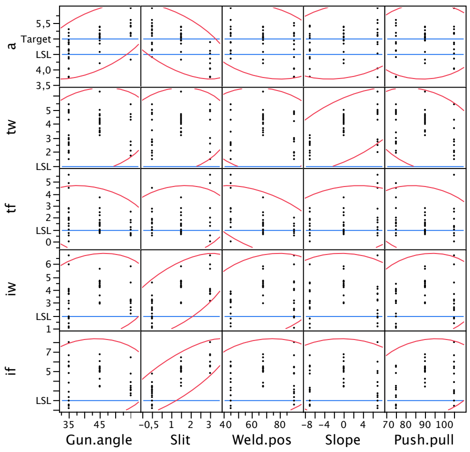
Bivariate relationships

Both existence and non-existence of bivariate relations between quality aspects give information. In Figure 7a, the output dimensions are plotted against each other.

Except the obvious relation between penetration on waist (iw) and flange (if) plates, there is no evidence of relationships. For instance, there is no relationship between penetrations (iw and if) and toe radiuses (tw and tf), and there is no proof of relationship between toe radiuses at different sides on the same weld. This is positive, since all parameters except penetrations can be met simultaneously. Figure 7b, shows relationships between each control parameter setting (x_i) and each resulting weld dimension (y_j). Except the weak correlation between Slit and penetration (iw and if), there are no simple relationships discernible. This will complicate process window determination by a one-factor-at-a-time approach.



a.



b.

Figure 7: Scatter plots of bivariate relationships: a.) shows cross variation relationships between resulting weld dimensions (y_j), b.) shows scatter plots matrix welding geometry parameters (x_i) versus each resulting weld dimension (y_j).

Corresponding scatter plots of the variation along weld, y.R (Appendix A) do not reveal any simple relationships at all between control parameters and variation. The variation along the weld is therefore treated as a fixed noise margin for each weld dimension respectively.

The conclusion from the bivariate analysis is that there is no simple relationship between control parameters and weld dimensions that requires a multi-parameter modelling approach. On the other hand, there are no relationships between the different weld dimensions either, except for the two measures on penetration, which opens up the possibility to optimize each dimension individually.

Modelling relationships

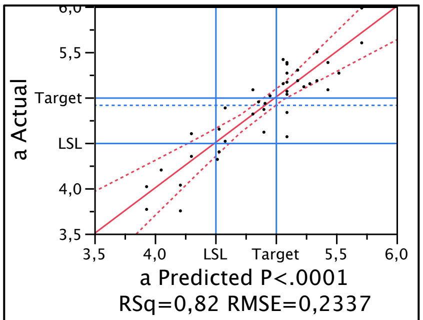
The multivariate model procedure here attempts to:

- develop models
  - revealing hot Xs for each quality aspects
- find overall 'best setting' by multi-parameter optimization
  - simultaneous usage of all models
- obtain optimal operating ranges for Xs
- carry out sensitivity analysis
  - by propagation of variation in hot X to variation in Y

Models

There is no absolute procedure for fitting a multi-parameter model to a data set. The Visual Six Sigma textbook [6] recommends scarcity effect principle, that is, not to add more terms to the model than reasonable to minimize the risk of over-fitting. The JMP® 10 software handles the excluded corner of the experimental plan.

The models are derived by standard least square regression and the number of factors are reduced following the procedure in Visual Six Sigma. Figure 8 shows a summary of the fitting of ‘a’, as an example. The models derived are listed below and a graphical profiler is shown in Figure 11 summarising the overall situation at a setting yielding maximum overall desirability.



RSquare	0,818758
RSquare Adj	0,781443
Root Mean Square Error	0,233702
Mean of Response	4,911905
Observations (or Sum Wgts)	42

Figure 8: Example of model fitting report showing predicted vs. actual for the weld dimension 'a'.

Derived prediction models y_i^{hat}:

- a^{hat} = -3.315 + 0.39 * Gun.angle + 1.22 * Slit + 0.02 * Slope - 0.0082 * Weld.pos - 0.0040 * Gun.angle^2 - 0.136 * Slit^2 - 0.029 * Gun.angle * Slit
- tw^{hat} = 6.287 + 0.143 * Slope - 0.0315 * Push.pull + 0.0175 * Gun.angle - 0.0046 * (Push.pull - 90) * (Push.pull - 90) + 0.002 * (Push.pull - 90) * (Gun.angle - 43.095)
- tf^{hat} = 6.212 - 0.038 * Weld.pos - 0.045 * Gun.angle + 0.044 * Slope - 0.0027 * (Weld.pos - 67.690) * Slope - 0.007 * (Gun.angle - 43.095) * Slope
- iw^{hat} = -2.812 + 0.999 * Slit + 0.089 * Gun.angle + 0.020 * Weld.pos
- if^{hat} = -3.899 + 1.406 * Slit + 0.091 * Gun.angle + 0.0283 * Push.pull

All models have R^2 above 0.60 (0.82, 0.76, 0.6, 0.74, and 0.85, respectively) and the residual analysis does not reveal any anomalies. The models are valid within the ranges defined in Figure 2, except the dangerous combination mentioned above.

Verification of models

To verify the prediction models in the most relevant area, five groups of three samples were produced at different settings than before. Four settings are assigned in the central of the model region and one in close proximity to the dangerous corner in order to double check the exclusion of the data points there. No verification measurement was able to question the models and the exclusion of the dangerous parameter combination. Figure 9 and Figure 10 show the prediction models and models derived from the verification measurements. The levels and slopes of the predicted verifications correspond well with the models. The prediction models are all inside the confidence interval of the verification models, making it impossible to reject the models with these verification measurements.

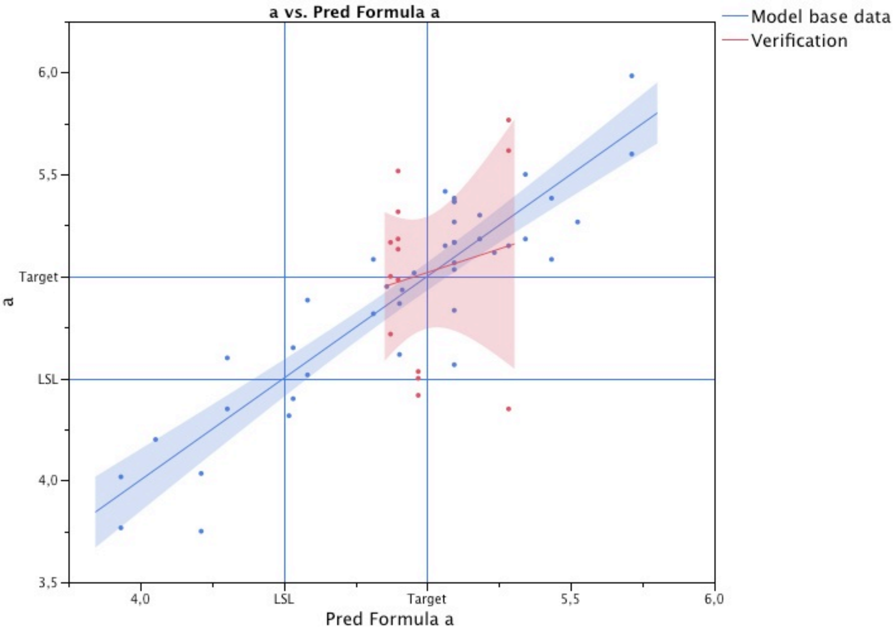


Figure 9: Predicting 'a' at other weld geometry settings agree were well with new verification measurements.

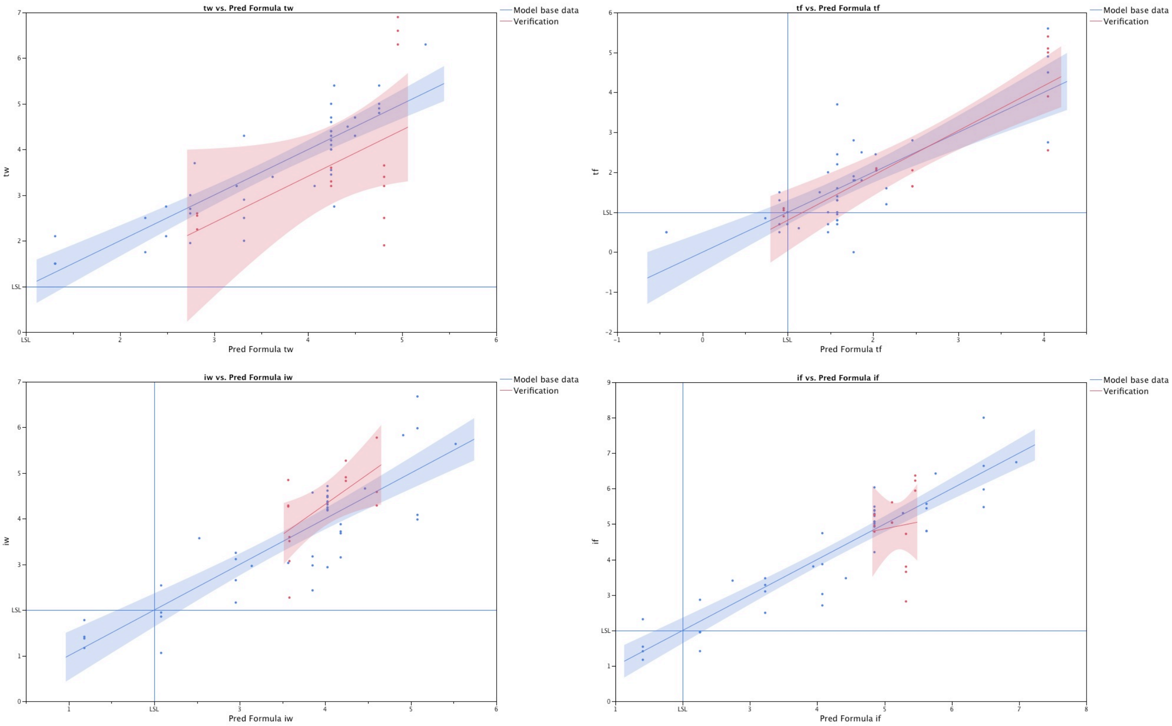


Figure 10: Verification measurements on the toe radiuses (tw and tf) and penetration (iw and if) agree well with the prediction models.

Sensitivity analysis

The overall maximized desirability in Figure 11 results in a setting of Slit of 2,4 mm, which is sensitive to variations in Slit. The desirability curve for Slit in the first column at the bottom row show a sharp peak at close to 2,4 mm. Slit is the control parameter that is most difficult to control and it would be preferable to find a more robust setting for that parameter. The lack of robustness for this setting is also indicated by the larger blue triangle.

By adjusting the settings in Figure 11 and study how the slopes of the responses changes, it is possible to identify a setting not so sensitive to variation (Figure 12). In Figure 13 the sensitivity to variations in control parameter settings has been predicted. Some variation in control parameters has been introduced to each parameter simulating process variation. In the example below the Slit is restricted to vary between 1,3 and 2,3 mm, the Gun.angle is set to 40°, N(40°, 3°), waist plate angle between [55°, 65°], Slope [-4°, 0] and Push.pull set to 90°, N(90°,3°), the simulation predicts that the welding will be within specification on all parameters with marginal for the variation along the welds.

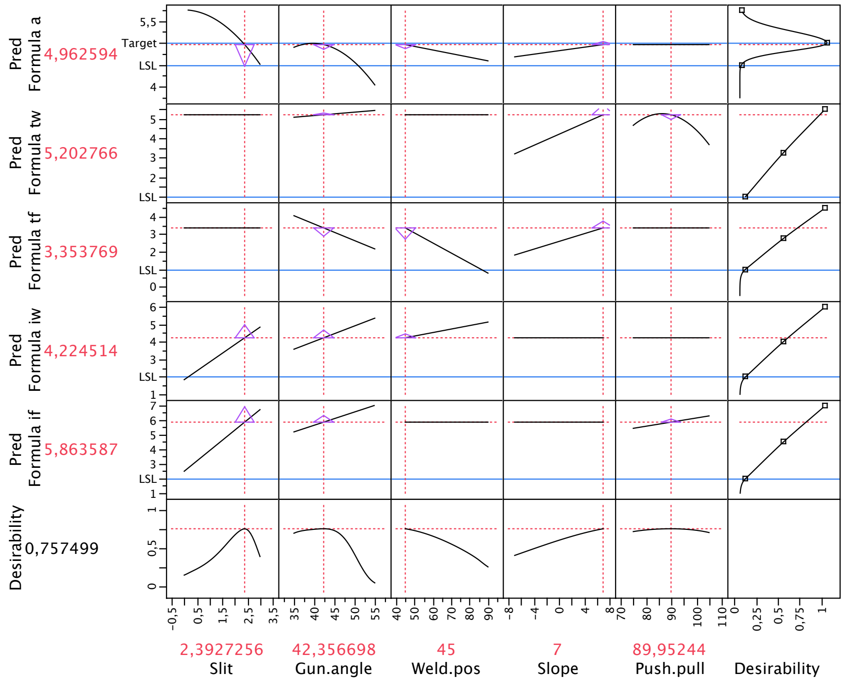


Figure 11: The profiler shows all models, one per row. The profiler has found a point in the parameter space that maximizes overall desirability by weighting the individual desirability's in the rightmost column. At the bottom row the sensitivity for each parameter is shown. At this setting the desirability is sensitive to variation of Slit, increases of weld.pos, etc. However adjusting the setting a more robust setting can be obtained as in Figure 12

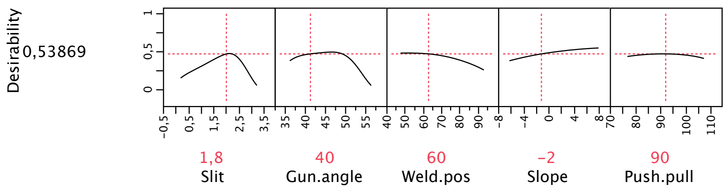


Figure 12: By adjusting the settings it is possible to find a position 'a not so' sensitive to any in variation in the control parameters without great loss in desirability.

Discussion and conclusion

A process window for robotized MAG welding that simultaneously fulfils all requirements on fillet weld bead dimensions (regarding thickness, penetration and toe radii at the bead/base material transition) for a particular welding case has been identified and studied by multi-parameter regression modelling. It allows for some variation of the welding geometry control parameters; taking variation along the welds into account.

Some interesting observations have been made during this project. The research question that arose after screening has not been rejected during the modelling phase:

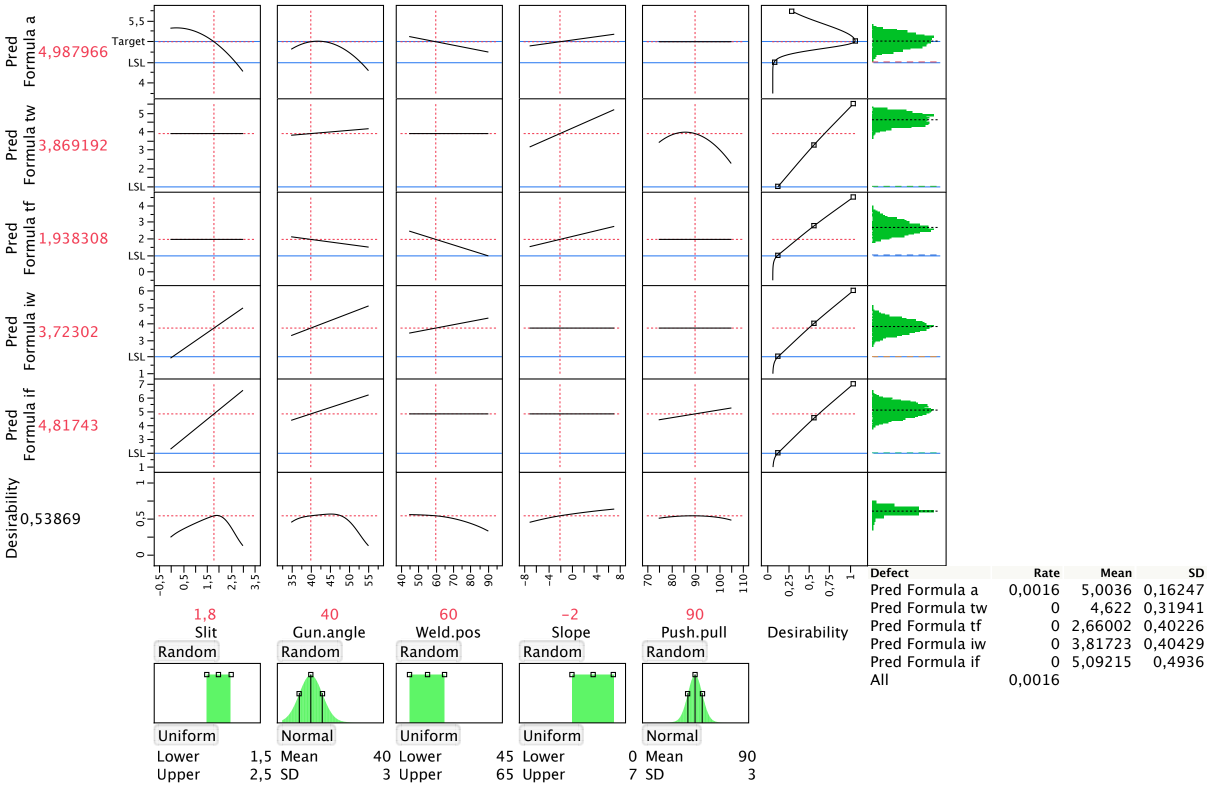


Figure 13: Assuming a reasonable process window for each control parameter the resulting distribution for each weld dimension are predicted to be within specification limits including the marginal for variation along the welds.

- Can the welding geometry parameters be used to compensate for bead geometry losses when productivity in the process is tuned up?

In this the welding geometry had stronger influence on final weld bead geometry than the weld arc and productivity parameters – meaning that the welding power (U and I), speed could be set to its normal productivity pace and the final bead geometry could be controlled by the welding geometry. If this result is generalizable, it may contribute to welding productivity increases without loss of quality, where controlling the welding geometry compensates for bead geometry losses due to higher productivity. However, it requires a multi-parameter optimisation approach since the there are no simple parameter relationships involved that require more advanced methodologies, such as, response surface methodology for model building or evolutionary operation (EVOP) to progressively develop productivity and quality together.

Another observation is that noise level in the system is high (process and measurement noise) reinforcing the need of a structured approach further. The verification models compared to the prediction models in Figure 9 and Figure 10 illustrate this. The verification data is collected in a narrow band blowing up the influence of noise and determination of model slopes become much more unsecure. This reinforces the general DoE recommendation to be bold when setting parameter levels for experimentation. To accurately determine the model coefficients two alternative routes are recommended; one is to use wider experimental ranges for off-line DoE and RSM modelling and the other is to collect more data for each experimental setting, using for example EVOP on-line, in order to suppress the influence of noise.

The modelling required a multi-parameter approach, since no simple relationships between control parameters and weld bead dimensions were found for this welding scenario.

Acknowledgement

We acknowledge both the time and input on the manuscript from Dr. Hendry Raharjo at Quality Sciences, Chalmers University of Technology.

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Appendix A

Occ	RunOrder	Control parameter experimental settings, x_i					Resulting Weld bead dimension, y_j Mean response [mm]					Variation along welds Range (max – min) [mm]				
		A. Gun.angle [°]	B. Slit [mm]	C. Weld.pos [°] (waist plate tilt Vertical direction is 90°)	D. Slope [°] (- up, + down)	E. Push.pull [°] (75° arc pull, 105° arc push)	a Bead thickness [mm]	tw Toe radius at waist plate [mm]	tf Toe radius at flange plate [mm]	iw Penetration at waist plate [mm]	if Penetration at flange plate [mm]	a.R [mm]	tw.R [mm]	tf.R [mm]	iw.R [mm]	if.R [mm]
1	1	35	3	90	7	75	3,75	4,90	2,00	4,08	4,80	1,43	1,50	1,00	1,70	2,13
1	2	55	0	90	-7	105	5,15	1,75	0,70	4,57	4,74	0,50	1,50	0,50	2,23	2,70
1	3	35	3	45	7	105	4,52	4,30	5,60	3,68	5,98	0,30	3,00	1,00	3,02	2,09
1	4	55	0	45	-7	75	5,08	2,10	1,80	3,11	3,28	-0,37	1,00	1,75	2,66	3,90
1	5	45	1,5	68	0	90	5,37	4,00	2,20	4,18	5,29	0,60	3,00	1,00	1,53	2,76
1	6	45	1,5	68	0	90	5,38	4,60	2,45	4,31	5,23	0,83	2,00	1,50	2,70	2,06
1	7	35	3	90	-7	105	4,02	1,50	0,50	5,98	6,64	0,97	0,00	0,00	2,62	2,22
1	8	55	0	45	7	105	5,98	5,40	1,20	3,25	3,87	-0,17	5,00	0,50	3,28	3,82
1	9	35	3	45	-7	75	4,60	2,60	2,80	3,88	5,57	0,53	2,00	4,50	1,83	3,45
1	10	55	0	90	7	75	5,50	4,70	0,50	3,17	3,47	0,67	3,00	0,00	2,57	3,33
2	11[3]	55	3	45	7	75	5,13	6,80	4,40	4,99	7,63	1,47	1,00	0,50	5,04	4,64
2	12	35	0	45	-7	105	4,87	2,10	1,90	1,78	1,95	1,07	3,50	2,50	1,38	1,17
2	13	45	1,5	68	0	90	5,27	4,30	1,40	4,62	5,27	0,27	2,00	0,75	3,68	2,65
2	14	35	0	90	7	105	4,82	2,90	1,00	1,86	1,95	0,77	3,50	0,00	2,03	2,52
2	15[3]	55	3	90	7	105	2,02	0,00	0,80	6,64	9,65	0,10	0,00	0,50	3,74	3,43
2	16	45	1,5	68	0	90	5,17	4,40	1,30	4,35	5,38	0,60	2,00	0,50	3,57	2,03
2	17[3]	55	3	90	-7	75	3,25	0,00	2,00	6,29	8,53	1,83	0,00	1,75	3,63	2,59
2	18	35	0	90	-7	75	4,40	1,95	1,50	1,06	1,54	1,00	1,25	0,00	1,92	1,84
2	19[3]	55	3	45	-7	105	2,42	1,40	1,40	5,60	11,81	4,83	7,00	7,00	5,55	7,59
2	20	35	0	45	7	75	5,18	5,00	4,50	1,17	1,17	0,90	4,00	3,00	1,80	1,84
3	21	55	0	45	-7	105	5,38	2,50	2,50	2,65	3,03	1,23	2,00	2,50	2,90	2,62
3	22	35	3	45	7	75	4,88	5,40	4,90	3,72	4,80	0,90	1,00	3,00	2,38	1,72
3	23	55	0	90	-7	75	5,42	2,75	1,00	2,98	3,10	0,57	0,50	0,00	1,60	2,79
3	24	35	3	90	7	105	4,03	2,00	0,50	6,68	8,00	0,20	5,50	0,00	1,64	2,20
3	25	45	1,5	68	0	90	5,07	4,10	0,80	4,38	5,06	0,20	1,00	0,50	4,20	3,71
3	26	45	1,5	68	0	90	5,03	4,70	0,70	4,71	5,49	0,13	0,50	3,00	2,63	3,65
3	27	55	0	45	7	75	5,60	4,30	1,60	2,16	2,50	0,67	4,50	1,50	3,27	2,99
3	28	35	3	90	-7	75	3,77	3,00	1,30	3,98	5,44	0,53	1,00	0,50	2,94	3,85
3	29	55	0	90	7	105	5,18	2,75	0,50	2,43	2,71	0,83	5,00	0,00	3,30	3,51
3	30	35	3	45	-7	105	4,35	1,50	0,00	3,15	5,48	0,90	5,00	5,00	3,94	3,57
4	31	35	0	90	-7	105	4,65	1,50	0,70	2,54	2,86	0,10	3,25	0,50	1,92	1,50
4	32[3]	55	3	90	7	75	3,95	3,90	-0,20	5,92	7,60	0,97	5,50	2,00	6,39	2,83
4	33	45	1,5	68	0	90	5,37	4,00	1,00	4,21	4,93	0,53	0,00	0,00	1,82	2,22
4	34[3]	55	3	45	-7	75	2,05	3,00	-0,30	5,09	9,52	2,70	5,00	5,50	4,34	8,34
4	35	35	0	45	-7	75	4,62	2,70	1,80	1,38	1,41	1,37	1,00	3,00	2,45	3,47
4	36	45	1,5	68	0	90	4,57	4,40	0,80	4,48	6,03	0,60	1,00	0,50	2,32	1,82
4	37	35	0	45	7	105	5,30	2,50	2,75	1,41	1,42	1,13	3,50	2,50	2,58	1,59
4	38[3]	55	3	45	7	105	-1,50	-2,00	-3,20	4,99	14,02	3,00	4,00	3,00	4,17	6,64
4	39	35	0	90	7	75	5,08	4,80	0,70	1,95	2,32	0,83	2,00	0,50	1,47	1,39
4	40[3]	55	3	90	-7	105	3,87	-0,90	0,90	6,64	8,90	0,80	0,50	1,00	3,23	3,75
5	41	35	1,5	68	0	90	4,95	3,20	2,45	2,97	3,81	0,43	1,00	1,00	2,63	1,96
5	42	55	1,5	68	0	90	4,32	4,50	0,60	5,83	6,43	0,70	3,00	0,50	2,16	1,77
5	43	45	0	68	0	90	5,27	3,55	0,95	3,57	3,41	0,73	1,75	0,75	2,71	2,03
5	44	45	3	68	0	90	4,20	5,00	1,60	5,64	6,75	0,40	2,00	1,00	1,66	1,70
5	45	45	1,5	45	0	90	5,15	3,45	2,80	3,03	4,21	1,17	3,25	2,50	1,78	2,68
5	46	45	1,5	90	0	90	4,93	4,20	0,85	4,66	5,39	0,80	1,50	0,75	3,53	1,97
5	47	45	1,5	68	-7	90	5,02	3,20	1,50	4,50	5,08	0,30	1,50	1,00	2,13	1,98
5	48	45	1,5	68	7	90	5,12	6,30	1,80	4,25	5,01	0,50	2,00	0,50	1,12	1,54
5	49	45	1,5	68	0	75	4,83	3,40	3,70	4,47	3,47	0,73	1,50	2,50	2,79	1,96
5	50	45	1,5	68	0	105	5,17	3,70	1,30	2,94	5,31	0,53	2,00	1,50	1,09	2,47

Verification data:

EE	1	35	2,4	45	7	94	5,18	1,90	2,55			0,83	1,75	1,25		
EE	2	35	2,4	45	7	94	4,98	2,50	5,00	3,60	3,80	0,63	3,00	4,50	2,40	2,35
EE	3	35	2,4	45	7	94	5,32	3,20	5,40	3,07	3,65	0,97	4,00	3,00	2,56	3,72
EE	4	35	2,4	45	7	94	5,13	3,40	3,90	3,51	4,72	0,47	3,50	2,00	2,01	2,60
EE	5	35	2,4	45	7	94	5,52	3,65	5,10	2,27	2,82	1,30	3,75	2,50	2,69	4,20
AA	6	45	1,5	45	0	90	5,62	3,20	1,65	4,85	5,26	0,90	2,50	1,00	3,11	2,09
AA	7	45	1,5	45	0	90	5,77	3,60	2,05	4,27	4,95	0,73	2,00	0,75	1,70	1,27
AA	8	45	1,5	45	0	90	4,35	3,30	1,65	4,29	4,79	0,70	2,50	1,25	1,75	2,44
BB	9	44,4	2,2	64,5	6,9	78,6	4,72	6,90	2,10	5,78	5,94	0,77	0,50	1,00	2,18	2,23
BB	10	44,4	2,2	64,5	6,9	78,6	5,17	6,60	2,05	4,59	6,37	0,20	1,00	3,00	1,72	3,63
BB	11	44,4	2,2	64,5	6,9	78,6	5,00	6,30	2,05	4,29	6,23	0,00	2,00	2,50	2,32	3,07
CC	12	43,3	1,5	86,3	0,4	104,7	4,50	2,55	1,10	5,27	5,61	0,60	1,25	1,00	3,56	3,93
CC	13	43,3	1,5	86,3	0,4	104,7	4,42	2,25	0,90	4,91	5,04	0,77	1,00	1,00	3,15	3,02
CC	14	43,3	1,5	86,3	0,4	104,7	4,53	2,60	1,05	4,83	5,05	0,93	1,00	0,75	4,64	3,61
DD	15[3]	55	3	75	0	105	4,10	2,15	1,40	4,34	5,70	0,27	2,25	1,75	2,69	3,48
DD	16[3]	55	3	75	0	105	4,18	2,30	1,10	4,93	5,99	0,70	1,25	1,00	4,18	6,06
DD	17[3]	55	3	75	0	105	4,22	1,95	1,50	4,63	5,59	0,17	1,50	0,75	3,47	5,53

[3] Outliers excluded before modelling belonging to the welding geometry combination: Gun.angle = 55° and Slit = 3 mm.