Statistical evaluation of welding quality in production

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Abstract

In this study the change in pre-conditions for quality/inspection are studied when the performance of an existing robotised welding process is improved using parameter design from robust design methodology. The findings are several. First, it was found that it is possible to build empirical response surface models of the key performance indicators measured that serves to improve the chances to find settings in the welding geometry that fulfil all requirements without increasing production cost. Secondly, it was also found that basic standard gauges and procedures for weld quality inspection easily are out-dated if not care is taken to investigate and improve all measurement systems used relative the actual variations occurring in the production. Thirdly, it was showed that improved welding performance will change pre-conditions for both product development and quality/inspection. Fourthly, ultrasonic P-scan has the potential to monitor penetration depth, but lower detection limits need to be further explored. Ultrasonic time-of-flight deflections his problems to monitor welding penetration depth less than 5mm on the present fillet weld set-up.

Introduction

The starting point for exploring the inspection strategy of inner welding errors[i] was a general uncertainty if the capacity of currently used non-destructive testing methods (NDT) can secure increasing demands of welding seam quality. In this investigation the natural variation in a robotized welding process is studied in order to find relationships between control parameters (input factors) and the output key performance indicators (KPI) for weld quality. The question is whether it is possible to find settings that improve quality without higher requirements on input tolerances[ii]. The basic idea origin from the define phase where it was revealed that development of 'risk based inspection' is an information development process where knowledge from several sources of variation need to be balanced. Product development supplies knowledge on likelihood of failure for different defects in difference zones in the product. Production supplies knowledge on process capability (C_{pk}). And quality/inspection supplies knowledge of probability of detection (POD). All factors interact in an overall estimate of risk vs. cost. And the risk of sub-optimization is overwhelming if these probabilities are treated separately. The need and prerequisite

[i] WP6 – Inspection strategy for inner welding error
[ii] Assuming that sharper tolerances always increase cost, from robust design theory

of a certain testing may change drastically if the setting of the process is changed and the distribution of type, size, location and frequency of the welding defects produced alters, for example. It is particularly important with a comprehensive approach in weight optimized structures since these variations can't be hidden by over dimensioning and broad margins. The qualitative characterization of this problem is worth its own discussion and presented in a parallel paper[1].

This investigation explores the natural variation in a robot welding process and discusses if and how it is possible to find settings that maximizing quality KPI and decreased variation without losing productivity and without upgrading the process by the use of parameter design including design of experiments. Is there a hidden sweet spot in the process that change the preconditions for quality and inspection? One important issue is to distinguish between variation in the welding process and variation in the measurement system used to monitor it.

The methodology used to tackle this problem was Six Sigma DMAIC. It stands for:

- Define: Characterization of the underlying problem through collection and analysis of qualitative and quantitative historical data with the purpose to validate or reformulate the problem statement and scope.
- Measure:
  - Securing that measurement system (MS) variability doesn't influence assessment of the processes monitored.
  - Process mapping, to identify process steps and input variables that influence the key performance indicator (KPI).
  - Sampling and measurements
- Analysis: Multi parameter exploration of the dependence between inputs and outputs.
- Improve: Parameter design of process and products in order to find the hidden improvements by changed settings that minimizes additional investments. Parameter design includes screening of influential factors (fractional design of experiments), full-factorial design of experiment to explore interactions and response surface methodology for optimization.
- Control: Correction and adjustment plans when process deviates from target.

Main sections

M-phase

The KPI of the welding quality defined in other work packages in this project are: a-height, i-depth (Figure 1) and fillet weld toe-radiuses. They are measured in the following way:

- a-height are measured with a-gauges, one for inspection in production and one for quality audit, Figure 2. The precision has been evaluated with measurement system analysis described below and a measurement procedure for the project was established.
- i-depth have been measured in two ways: non-destructively with ultrasonic through the flange plate, and destructively by breaking the weld and measuring the penetration depth from a mark on the flange plate of the of back surface of the waist plate, Figure 8. Accuracy between the methods were evaluated and adjusted, which is described below.
- Toe-radius was measured by fitting radius gauges (one operator).

Measurement system analysis (MSA)

It is important to check whether the measurement system (MS) used for process monitoring and development have high enough precision in order to detect variations in the process key performance indicator (KPI) monitored. The precision of a capable MS is 10 times better than the process it monitors, as a rule of thumb. That is, if one is measuring in the millimetre range, the MS precision should be in the 1/10 millimetre range. Measurement system analysis is a standard procedure to determine if measurement system (MS) precision (repeatability and reproducibility) is good enough relative process variation. The standard requirement for a MS used for go/no go decisions in production is that it cannot add more the 9% of the total variation (process variation + MS variation) in terms of %Contribution. A MS used for process development cannot add more than 4% of the total variation). MSA checks MS precision (scatter in terms of standard deviation) not to be mistaken for MS accuracy (mean level) that is checked with normal calibration. Just because the MS show the right mean compared to a reference doesn't mean it doesn't drown process variations with measurement noise. MSA identifies sources of noise and instability in the MS that is difficult without specific procedure.

MSA fillet weld a-height gauge

Introduction

The measurement system (gauge + procedure) analysed is used for quality assurance and process control of fillet weld a-height [mm], defined in Figure 1, used in Volvo CE Arvika and Braås in robot welding processes in production of frames for wheel loaders and articulated haulers. The purpose with the MSA is to determine the precision of the MS in relation to the welding process capability, C_{pk}.
The result shows that the MS is bad in its present configuration. It cannot see any difference in the welds with 5 mm a-height produced. It has direct impact on production cost, since thicker welds than necessary are produced. The reason is that the high scatter in the MS has driven an increased setting of the process target. Instead of keeping a setting to produce a process target of a-height at 5mm, the large total scatter seen, sum of process scatter and measurement scatter, induce a setting of the process target at almost 6mm; in order to avoid waste and rework with welds under the lower specification limit (LSL) of 4,5mm.

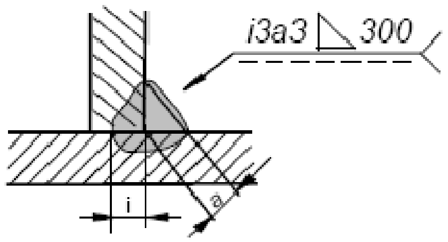

Figure 1: Definition of a-height and i-depth on fillet weld, example.

Figure 2: a) Measurement principle audit gauge, a-height [mm], b) audit gauge – calculates a-height from measured position of weld toe, c) production inspection gauge, measure a-height directly on weld ridge (45 deg from base plate).

Figure 2 show the gauges analysed and how the measurement procedure is. Two types of gauges are used. One gauge b) used at quality audit and one gauge c) used by welding process operators. The latter are considered easier to use, but give values on the weld ridge that may deviate from the true a-height since the weld surface may be either concave or convex. This difference can be seen in Figure 3. The difference between production gauge and audit gauge for the frame in Braås (the two right groups) depends on tube thread welding. Compared to solid thread welding used in Arvika where the weld surface are more flat give the metal cored wire welding convex weld ridge. This difference is however part of a calibration routine that adjusts the MS accuracy (mean value). Measurement system analysis (MSA) determines the precision, that is, the measurement noise in terms of reproducibility and repeatability.

MSA details

Three MSA where executed with both gauges, six in total, on three randomly picked frames. On each frame were 5 welds with drawing specification a-height 5mm chosen. The drawback with this procedure was that the variation between welds on the same frame may reflect the short term variation in the welding process but not the long term variation. Ideally 5 welds on different frames produced with a time gap would have been used, but that was not practically solved in this project. The purpose with the MSA was first-hand to secure a MS for the project. The mean ranges on the three frames are 1.2 mm. That is, the difference between the thickest and the thinnest weld on the same frame is on average 1.2 mm, for 5mm nominal welds. This is seen in Figure 3 as the difference between the highest and the lowest dot for ‘Pr’ for each frame. Each weld is measured by each operator three times in a random order.

In the first pair (both gauges) of MSAs executed, the audit gauge on the first frame in Arvika (Ar/1 Rev), second group, shows significantly higher variability than the production inspection gauge. The measurements range from 2mm to over 7mm, whereas the production inspection gauge measurements range from 5 to 6.5 mm. The major source of variation in this case (¾) come from the reproducibility. That is, different operators do differently. After an update on operator instructions a second pair of MSA was execute Ar/2 on a new frame, resulting on similar variability for both gauges.

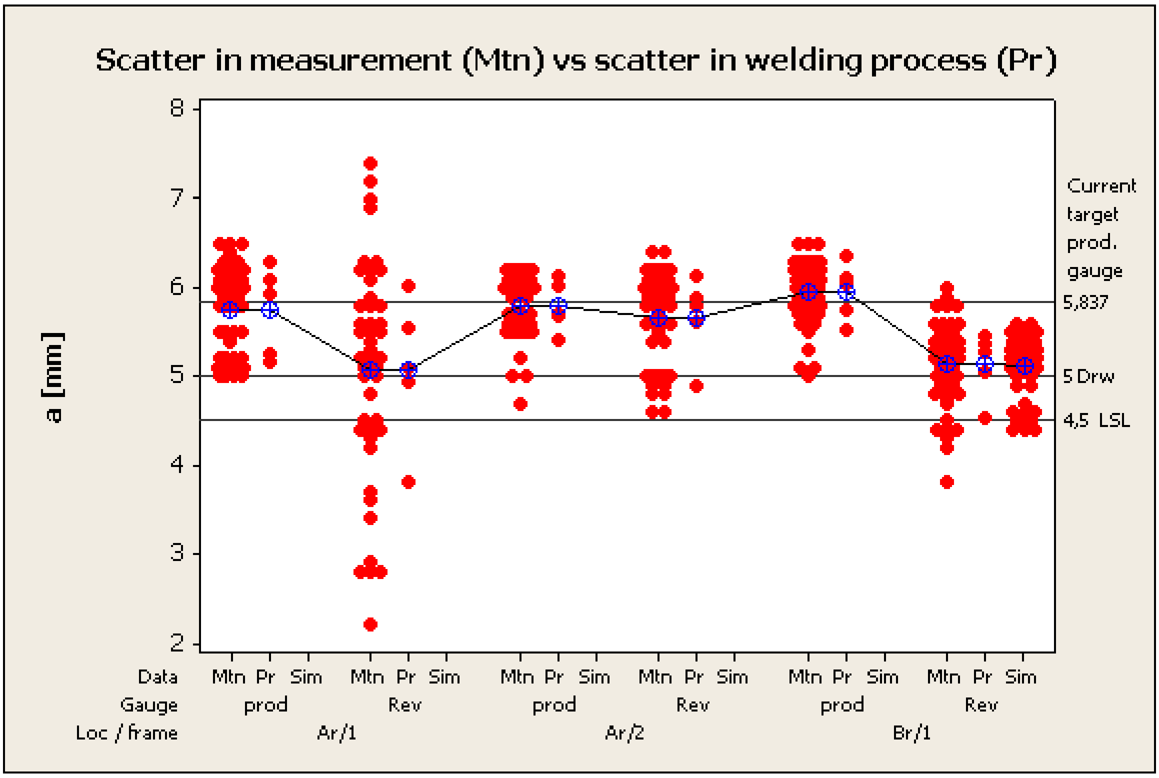

Figure 3: Summary of three MSA on audit gauge and three on production gauge.

In Figure 4 and Figure 5 is the result of the audit gauge MSA in Braås discussed, the rightmost group in Figure 3. The %Contribution for this MS is 58.30% (top right figure in Figure 4). It means that the MS contribute with almost 60% of the total variation seen. Compared to the tolerance, the measurement noise is 55% of the tolerance width. To make go/no-go decisions the MS noise has to be less than 30% of the tolerance width and less 9% of total variation (%Contribution). The total blurriness of the gauge results in only 1 discrimination level within the tolerance band. That is, the MS precision is in the same range as the process precision. The recommended number of discrimination levels is more than 7. The main part of the lack of precision is still coming from lack of reproducibility (44%) whereas the gauge itself adds 14% variability of lack of repeatability. This in itself is still too large for go/no-go decisions (>9%) and far out for process development (>4%).

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0,170148	58,30
Repeatability	0,040889	14,01
Reproducibility	0,129259	44,29
Braås operat	0,088500	30,32
Braås operat*Braås weld s	0,040759	13,96
Part-To-Part	0,121722	41,70
Total Variation	0,291870	100,00

Process tolerance = 4,5

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)	%Tolerance (SV/Toler)
Total Gage R&R	0,412490	2,47494	76,35	55,00
Repeatability	0,202210	1,21326	37,43	26,96
Reproducibility	0,359526	2,15716	66,55	47,94
Braås operat	0,297489	1,78494	55,07	39,67
Braås operat*Braås weld s	0,201889	1,21134	37,37	26,92
Part-To-Part	0,348887	2,09332	64,58	46,52
Total Variation	0,540250	3,24150	100,00	72,03

Number of Distinct Categories = 1

Figure 4: Result of MSA on the audit gauge at Braås, Br/1

In Figure 5 details of the MSA can be seen:

- Top left: graphical summary of the total – the gage r&R is larger than the part-to-part variation
- Mid left: Individual range per operator and weld – it show stability of the MS. In this case is there a point over the upper specification limit for the second weld for B_Kalle operator. It means that the MS is not stable over time and the recommendation is not to use this MS until stability over time is secured. The MS is not trustworthy in its present configuration.
- Low left: Mean measure per weld for each operator. Each operator should have similar profile of the five welds. And more than half of the dots should be on the outside of the control limits (red lines). The band between the red lines symbolizes the blurriness of the system.
- Top right: All measurements on each weld. The difference between welds should be large compared to the range of the measurements on each weld if should be possible to see any difference between them.
- Mid right: Measurements per operator. Mean for all operators should be the same. In this case measures B_Ludvig thicker welds than the others.
- Low right: Interaction between operator and part. Parallel lines preferred. Here operators measure some welds systematically different.

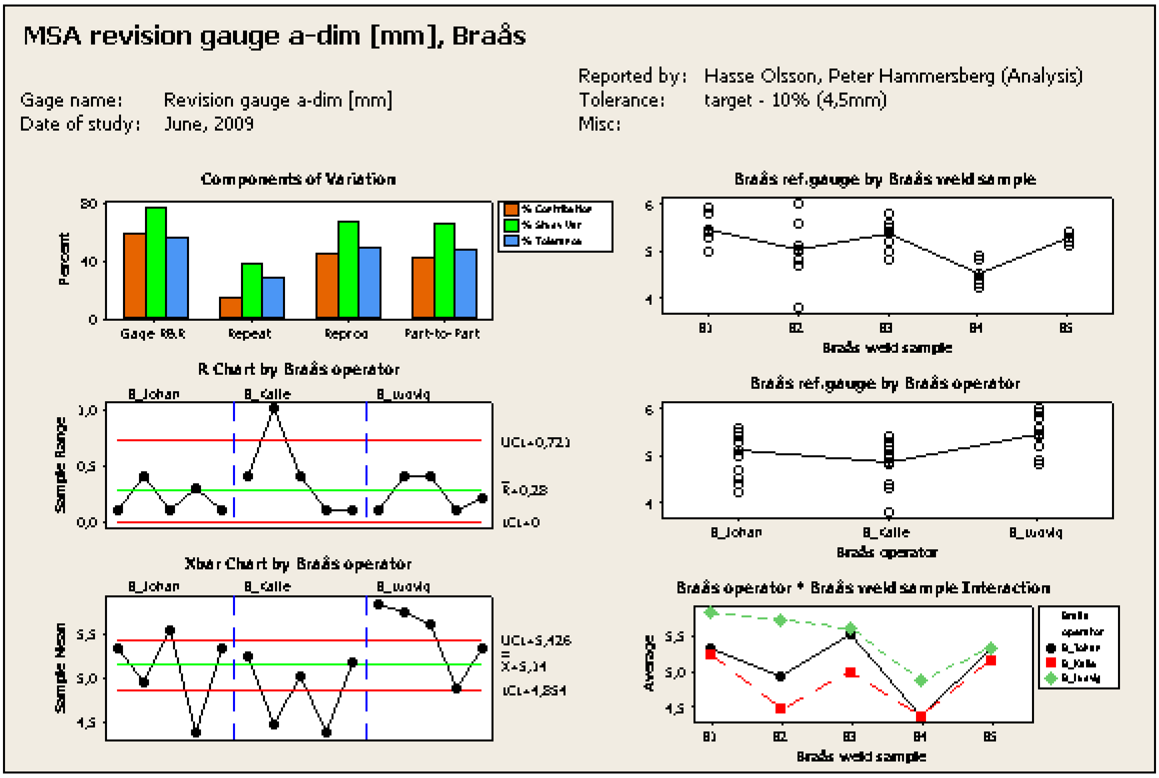

Figure 5: Graphical presentation of the Gauge r&R in Figure 4

Summary of a-height gauge

Figure 6 show the schematic consequence of large scatter in the MS. The operator only sees the total variation of welding process and measurement noise together in the lower curve. Commonly all this variation perceives to come from the process, if not MSA is a standard operation procedure used to separate variation components. Intuitively the welding process looks much worse than it is. To avoid waste and reworking welds measured to be less than 4.5 mm the settings for process a-height target is adjusted upwards. In Figure 3 it can be seen that the mean weld a-height measured with the production gauge (the one closest to process operators) is 5,8mm for these randomly chosen frames, which is at least 0,5mm more than necessary if the welds been measured with an ideal MS. The t-test in Figure 7 confirms that the settings of the targets both in Arvika and Braås are statistically significantly higher than 5.0 mm for these randomly chosen frames.

The rightmost dots in Figure 3 are simulated measurements on the Br/1 frame with MS approved for production inspection, adding max 9% to the total variation.

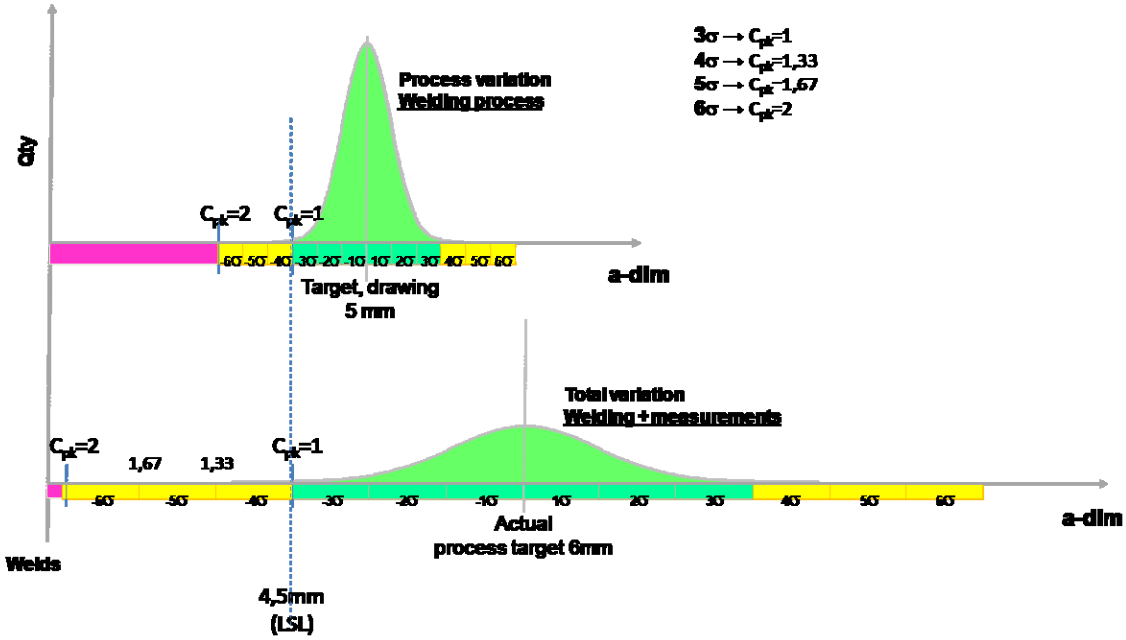

Figure 6: Consequence of large measurement system noise with fixed lower specific limit (LSL)

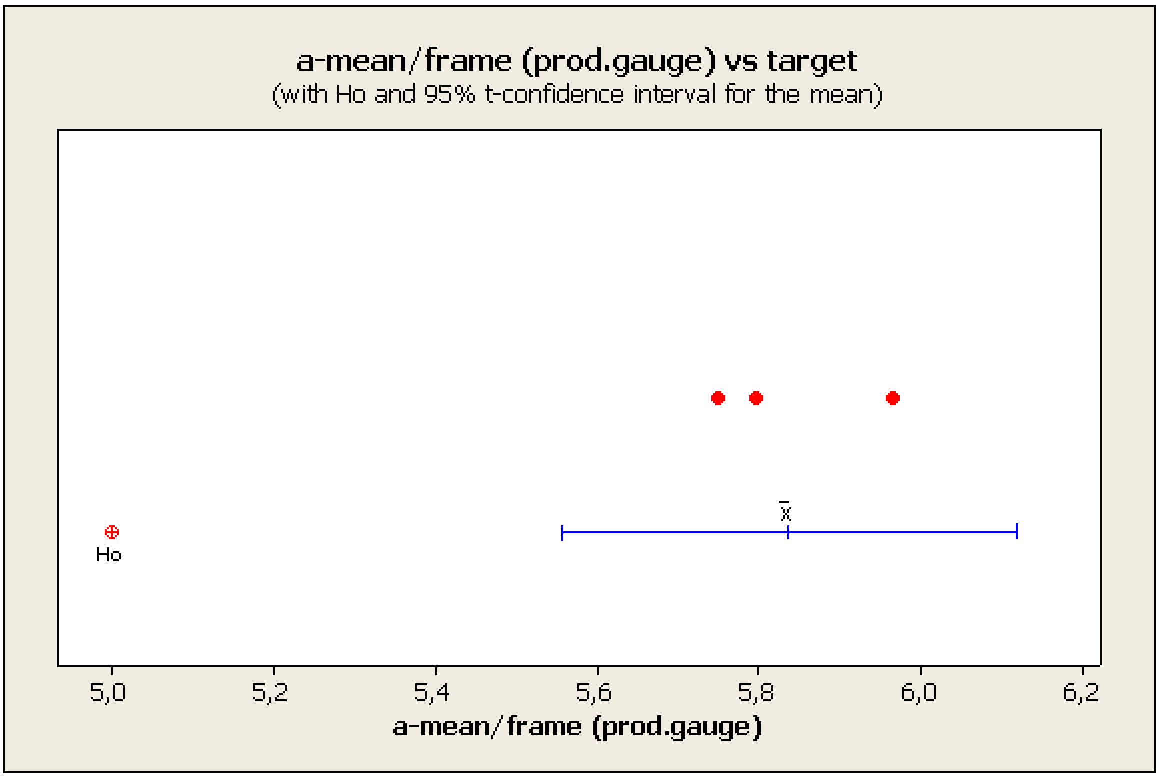

Figure 7: One sample t-test to test if mean of selected welds is 5.0 mm or not. Result: Drawing target of 5.0 mm is outside confidence interval (p=0,006) for the mean of selected welds.

MSA summary

With an ideal MS the welding process target setting is 5,4mm to keep a distance to the lower specification limit of C_{pk}=1. That is, 3 standard deviation of the process variation. The lack of precision in the measurement system has a direct impact of manufacturing cost since 0.5 mm more a-height than is shipped. In total 30-40%

more weld volume than specified is produced. The 0.4 mm of target is added by the lack of precision in the welding process, which raises the question if there is a setting for the process that minimizes variation and meet requirements on target simultaneously.

To continue the project to determine the welding process performance the a-height was measured by one operator that measured each weld position three times at each position calculating a mean.

i-depth measurements

Non-destructive measurements with ultrasonic testing (FORCE) were compared to destructive measurements (Volvo CE, Arvika). The ultrasonic methods tested were: Time-of-flight Deflection (TofD) and Bottom pulse echo (P-scan). Figure 8 shows the schematic set up. 20 samples welded with different settings were investigated. Figure 9 show example of the difference between P-scan and TofD of the same reference sample. The pre-fabricated slits are well determined with P-scan and also by TofD if penetration depth larger than 5mm, otherwise is the angle to small. The correspondence between weld profiles measure with P-scan and destructive measurements are good after adjustment of the marking procedure. Further analysis is required to determine the smallest i-depth variation that P-scan can detect.

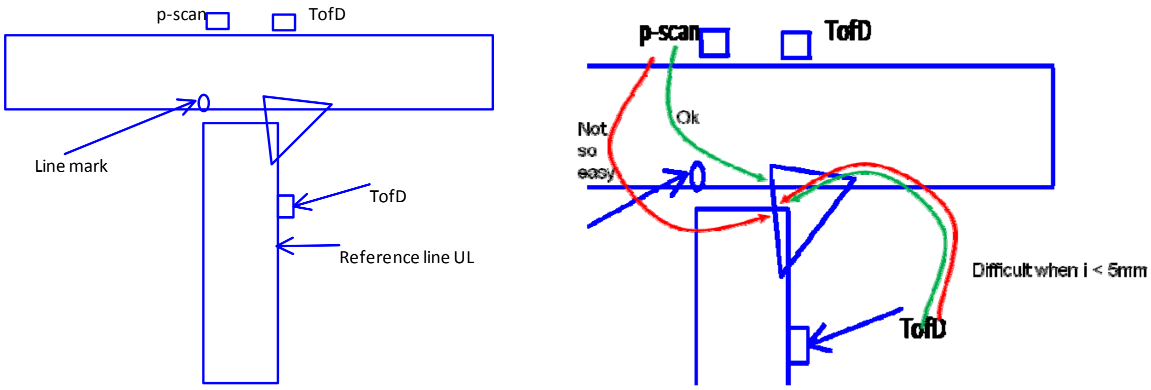

Figure 8: Schematic set up of UL and destructive comparison

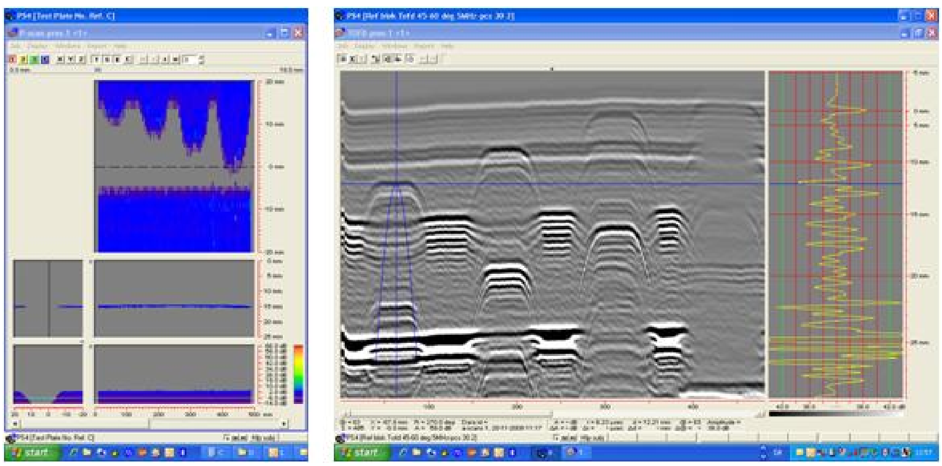

Figure 9: P-scan determine where weld seam is in contact with backside of the flange plate (left). TofD is difficult when i-depth is below 5mm (right).

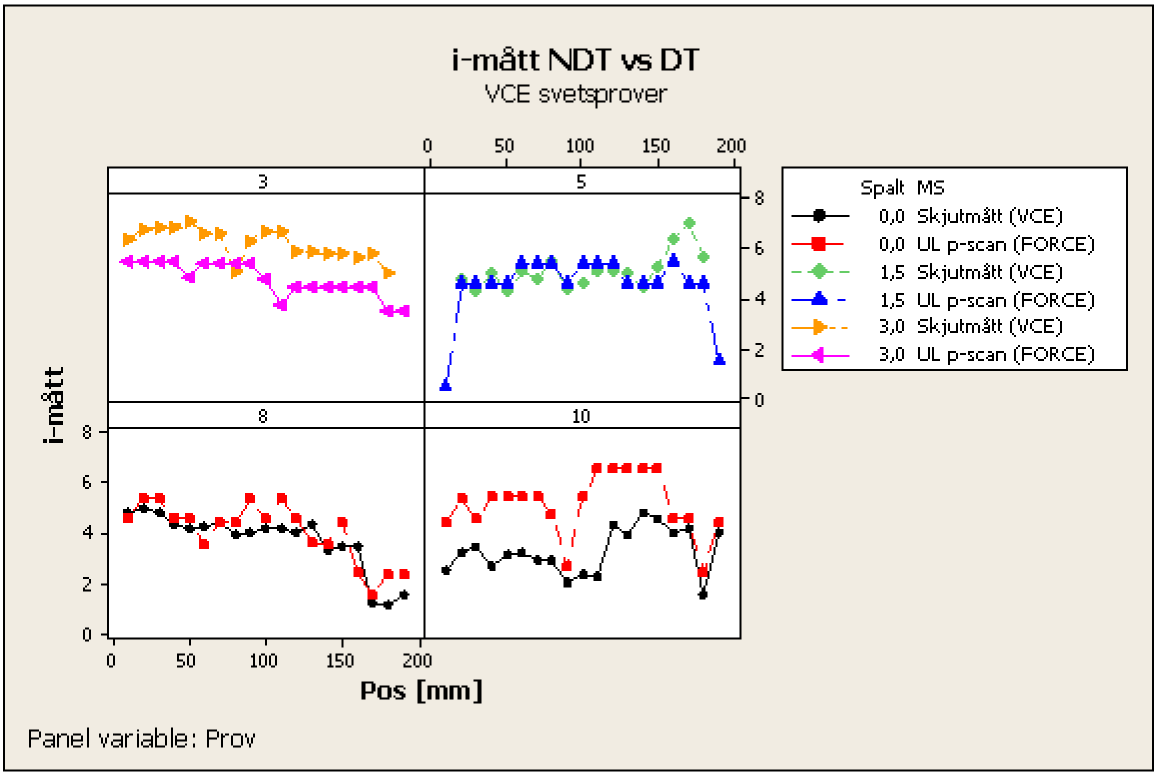

Figure 10: Profiles of P-scan and destructive testing. Profiles correspond, but the first samples show different levels depending on the slit. It required adjustment of the marking procedure.

Assessment of variations in a robot welding process

Introduction

The process capabilities of the KPI for weld life in the welding process are central input knowledge for risk-based inspection development. And to know what parameters and how they influence the process capability have two distinct reasons. First, by exploring the welding system using parameter design methodology[3] and EVOP[4] (evolutionary operation) building a multi parameter model of the transfer function it is possible to improve the welding process performance and to find robust and ideal operating conditions to achieve optimum output (response). For the actual process it means to find settings of the process that maximize fillet weld toe radiuses[iii] and weld penetration depth (i) while keeping the a-height at 5mm and minimizing variation along the weld. Secondly, the level of natural variation in the process determined will set the requirement for the measurement and inspection systems used to monitor it.

When optimising the setting of the process both occurrence and seriousness of critical defects will change that, in its turn, will change the preconditions both for product development dimension and the resolution and sampling requirement for inspection.

The following roadmap for multi parameter experimentation has been followed within the DMAIC analysis and improvement phases:

[iii] Fatigue crack initiation is depending on weld toe radius. The sharper the radius the more easily fatigue cracks start to grow.

- Process mapping resulted in a gross list of 24 relevant control parameters in the welding process
- Cause&effect analysis identified 11 of the 24 as potential control parameters influencing the welding quality
- Screening experiment with a saturated fractional two-level factors design separated further 6 parameters with limited influence (16run+4 centre points)
- Parameter interaction and curvature was identified with a full-factorial design for 5 parameters with 32 experimental runs plus 8 centre points
- Models for a-height, i-depth[iv], fillet weld toe radiuses and their respective variation along the weld were determination with response surface methodology with 10 axial point runs.
- Verification was done by finding a setting fulfilling all requirements using Excel Solver which was then used to weld 5 samples.

Details

Figure 8 show a p-diagram of the welding process, after qualitative mapping and screening. To the left, the input signals are listed to produce a fillet weld with 5mm a-height and 2mm i-depth, defined in Figure 1, and the settings of the welding process that were fixed after the screening phase to nominal or most practical settings for production of a-height 5 mm. To the right the intended and unintended (error) output signals were defined. Noise factors, below, were not considered here. In the top, the control parameters and their experimental range are listed, respectively. The five most important parameters identified during the screening stage influencing the output responses are:

A. welding pistol (torch) angle perpendicular to the weld seam
B. slit between waist plate end and flange plate
C. waist plate angle – the arrangement of the plates when weld together can vary between (1) vertical waist plate / horizontal flange (90) and (2) both plates at + and – 45 degrees
D. uphill welding (-) downhill welding (+)
E. pistol (torch) angle over seam (lower angle means pistol in front of weld point, higher degree pistol behind weld point).

[iv] The i-depth model is currently under finalization. It will probably shift the optimal setting, but not the routine.

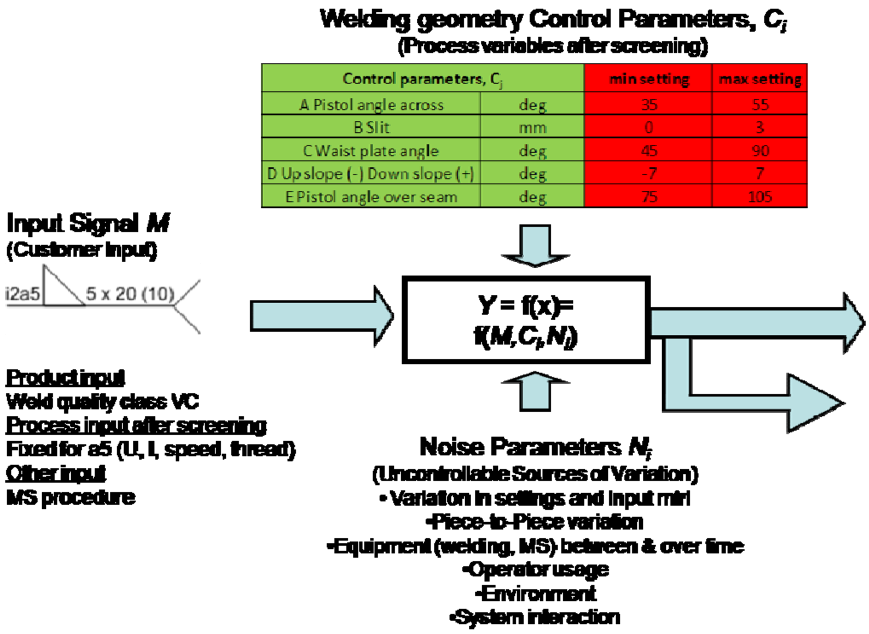

Figure 11: Welding process p-diagram illustrates the categories of parameters influencing accuracy and precision of the output responses.

Result model building

Figure 12 show the main effects on a-height and the fitting of a regression model to the full factorial 5 factor experiments. The centre point is not captured meaning that higher order terms (x^2) need to be estimated by adding axial points to the experimental design making it into a central composite design.

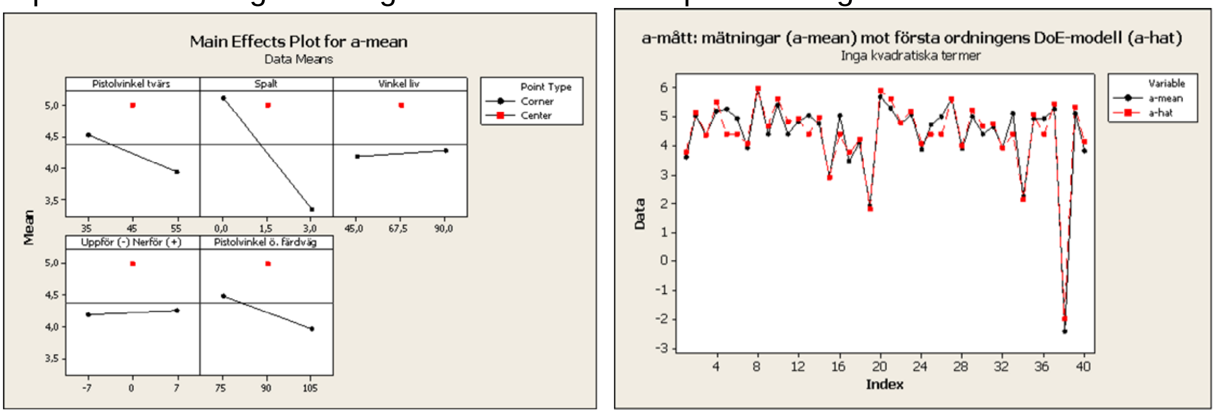

Figure 12: Fitting a first-order model to the a-height measurements. Up to four factor interactions is active, R^2 > 80%, but center point is not captured

Figure 13 shows the fitting of the full second order model to the experimental data. More than 97% of the variation in the data is explained by the model. It requires both second order terms (x^2) and interactions with several parameters. This is unusual, the standard procedure is to exclude 3 factor interactions and higher, but in welding and certain complicated chemical processes, for example, it occurs[2]. The existence of higher factor interactions suggest complicated physical relations during the welding fusion; electrical, magnetic and gravitation forces, component geometry, materials, environmental and process geometry and settings and more all interact. The response surface methodology doesn't explain the physics, but it supplies a methodology that may support studies and understanding of the physics and effectively helps to find robust settings from few experiments in existing and new production processes. Figure 14 shows the rsm (respons surface methodologies) model for the all output responses except i-depth.

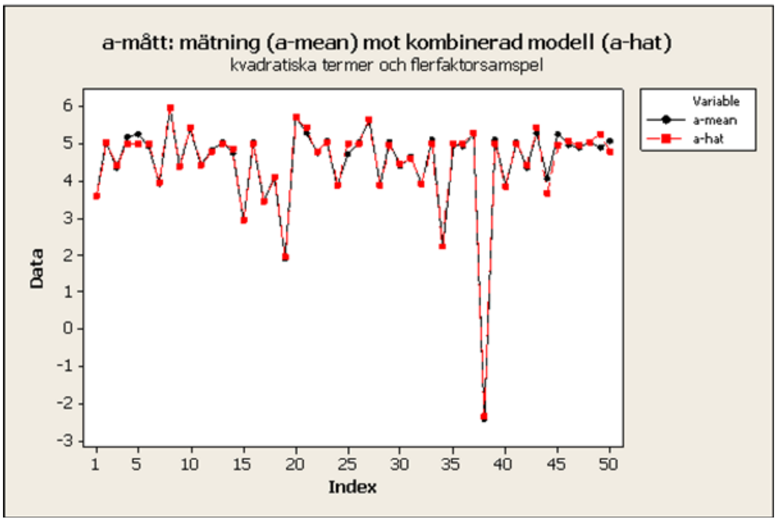

Figure 13: Fitting of second order response surface model (R2 > 97%). The model to predict a-height requires 29 significant parameters.

a-mean = 12,0 - 10,7 B Slit - 0,184 C Waist plate angle
- 0,136 E Pistol angle over seam + 0,308 AB + 0,00392 AC + 0,00307 AE
+ 0,126 BC - 1,13 BD + 0,161 BE + 0,00302 CD + 0,00184 CE - 0,00352 ABC
+ 0,0347 ABD - 0,00448 ABE - 0,000031 ACD - 0,000042 ACE + 0,000015 ADE
+ 0,00905 BCD - 0,00177 BCE + 0,0138 BDE - 0,000022 CDE - 0,000312 ABCD
+ 0,000049 ABCE - 0,000423 ABDE - 0,000119 BCDE + 0,000004 ABCDE
- 0,00298 AA - 0,210 BB

a-range = 8,27 - 0,0781 A Pistol angle across - 0,117 C Waist plate angle
- 0,515 D Up slope (-) down slope (+) + 0,0180 AD - 0,0289 BC + 0,517 BD
- 0,0535 BE - 0,000567 CE + 0,00845 DE + 0,000657 ABC - 0,0163 ABD
+ 0,00138 ABE - 0,000131 ACD + 0,000010 ACE - 0,000265 ADE
+ 0,000880 BCE - 0,00555 BDE - 0,000033 CDE + 0,000077 ABCD
- 0,000022 ABCE + 0,000166 ABDE + 0,000002 ACDE - 0,000001 ABCDE
+ 0,000924 CC + 0,00377 DD

toe_waist_ mean = - 3,74 - 20,9 B Slit + 0,140 D Up slope (-) Down slope (+) + 0,570 AB
+ 0,00565 AC + 0,00632 AE + 0,250 BC - 0,468 BD + 0,244 BE
+ 0,00232 CE - 0,00657 ABC + 0,0149 ABD - 0,00655 ABE
- 0,000068 ACE - 0,00273 BCE + 0,00910 BDE + 0,000071 ABCE
- 0,000257 ABDE - 0,000053 BCDE + 0,000001 ABCDE - 0,00572 AA
- 0,00145 CC - 0,00144 EE

toe_waist_range = 12,0 - 0,345 C Waist plate angle + 0,306 D Up slope (-) Down slope (+)
- 0,111 AB - 0,0725 BC + 2,28 BD - 0,0244 BE + 0,000595 CE
- 0,00577 DE + 0,00331 ABC - 0,0577 ABD + 0,00191 ABE
+ 0,000088 ADE - 0,0446 BCD + 0,00108 BCE - 0,0245 BDE
+ 0,00107 ABCD - 0,000045 ABCE + 0,000566 ABDE + 0,000507 BCDE
- 0,000011 ABCDE + 0,00206 CC

toe_flange_mean = 25,4 - 0,0325 C Waist plate angle + 1,67 D Up slope (-) Down slope (+)
- 0,460 E Pistol angle above seam + 0,0823 AB - 0,0177 AD
- 4,23 BD + 0,0446 BE - 0,0203 CD - 0,00869 DE - 0,000702 ABC
+ 0,100 ABD - 0,00179 ABE + 0,000192 ACD + 0,0528 BCD
- 0,000460 BCE + 0,0485 BDE + 0,000115 CDE - 0,00124 ABCD
+ 0,000019 ABCE - 0,00113 ABDE - 0,000594 BCDE + 0,000014 ABCDE
- 0,000408 AA - 0,225 BB + 0,00248 EE

toe_flange_range = 37,3 + 9,75 B Slit - 0,0982 C Waist plate angle
- 0,691 E Pistol angle over seam - 0,250 AB + 0,00123 AC
- 0,115 BC + 1,22 BD - 0,122 BE + 0,00318 ABC - 0,0296 ABD
+ 0,00326 ABE + 0,000024 ACD - 0,000025 ADE - 0,0133 BCD
+ 0,00135 BCE - 0,0136 BDE + 0,000326 ABCD - 0,000039 ABCE
+ 0,000296 ABDE + 0,000151 BCDE - 0,000003 ABCDE - 0,00131 AA
+ 0,00381 EE

Figure 14: Fitted rsm models for a-height, a-range along weld, toe radiuses and ranges except for i-depth.

Verification

With excel solver a setting was found that fulfilled the requirements on all models above. It may still be a local optimum illustrated in Figure 15, but it serves as verification of the methodology. Further analysis of optimum and robustness needs to be performed including the models for i-depth. In Figure 16 settings fulfilling all requirements is found together with the result of the verification welding at the bottom. The settings found with Solver produced a-heights of 5,2mm with a LCL of 4,8mm. The toe radius produced is shown in Figure 17. The mean toe radius is well above the requirement on 1mm for VC-classed welds. The variation along the welds is low but the variation between welds is still high. This parameter needs to be feed to the Solver calculation along with the model for i-depth in the next stage of this work.

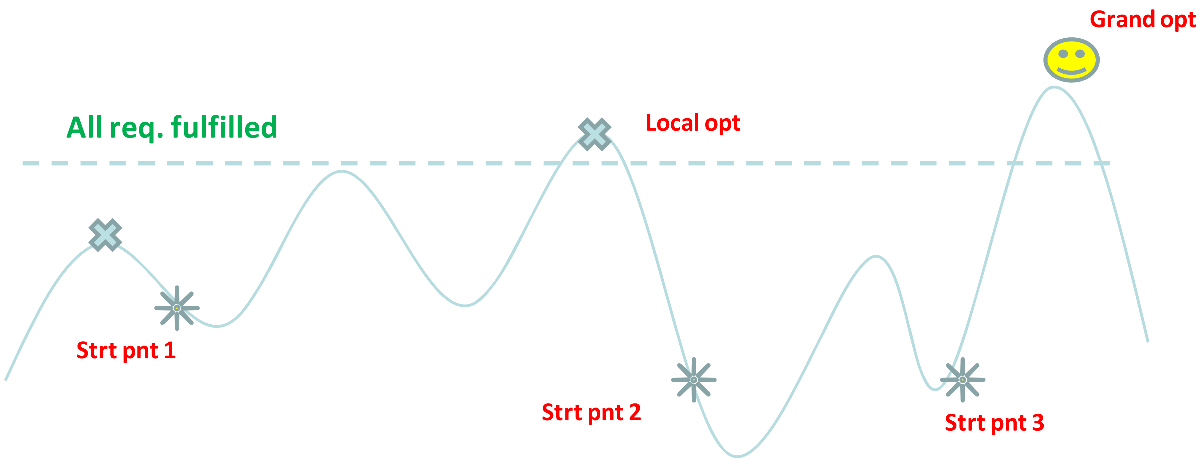

Figure 15: Illustration of local optimum fullfilling requirements

Control parameters, C_j		**min setting**	**max setting**		**Settings fulfilling requirements**
A Pistol angle across	deg	35	55		35,0
B Slit	mm	0	3		2,4
C Waist plate angle	deg	45	90		45,0
D Up slope (-) Down slope (+)	deg	-7	7		7,0
E Pistol angle over seam	deg	75	105		93,9

Target (requirement)	min a-height [mm]	i-depth [mm]	toe radius waist [mm]	tå radius flange [mm] > toe radius waist - x
				1,00
Target Y:	5	2	max	4,8
LSL (lower spec limit) [mm]	4,5		1,0	1,0
Range Y (process variation max-min):	1,0			

Calculation results	a-height [mm]	i-depth [mm]	toe radius waist [mm]	toe radius flange [mm]
Mean Y:	5,0		4,8	4,8
LCL (lower control limit)	4,6		3,6	4,3
Range Y (process variation max-min):	0,8		2,5	1,1

Sensitivity (partiell derivative):		a-height [mm]	i-depth [mm]	toe radius waist [mm]	tå radius flange [mm]
A	dY/dA	-0,1		0,0	-0,2
	d(Yrange)/dA	0,1		0,0	0,0
B	dY/dB	-0,7		-0,9	0,3
	d(Yrange)/dB	-0,3		-0,4	-0,2
C	dY/dC	0,0		0,0	-0,9
	d(Yrange)/dC	0,0		-0,1	0,0
D	dY/dD	0,0		0,2	0,3
	d(Yrange)/dD	0,0		-0,1	-0,2
E	dY/dE	0,0		-0,1	0,0
	d(Yrange)/dE	0,0		0,1	0,0

VERIFICATION	a-height [mm]	i-depth [mm]	toe radius waist [mm]	toe radius flange [mm]
Mean Y:	5,2		2,9	4,4
LCL	4,8		1,3	3,1
Range Y (process variation max-min):	0,8		3,2	2,7

Figure 16: Example of layout in excel solver. While changing settings of control parameters A-E with their range the calculation run until requirements (blue) are fulfilled. Sensitivity is calculated with the partial derivative, but no requirements are put on the gradient in present set-up. The most reddish figure shows the steepest slope of the response surface for that variable for this setting.

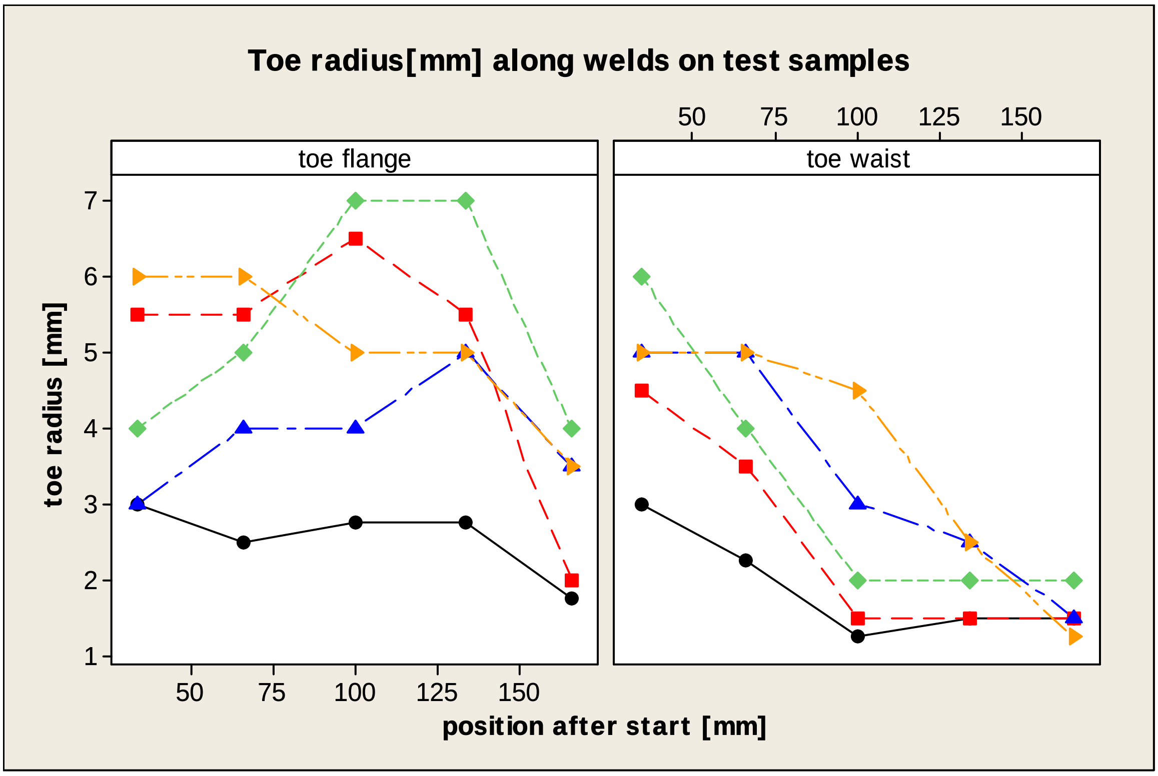

Figure 17: Verification welds with settings fulfilling requirements. The toe radius is well above 1mm on the flange (left). The variation along the weld is low, but the variation between the welds is large. This variation was however not included in the present set up of Solver. The toe radius on the waist starts on the same level as on the flange but decrease along the weld. This needs further examination.

Discussion

Welding is a complex process. The physics of what happens in the welding spot is not fully understood. However the methodology shown here is a support when improving performance in existing welding processes. And also helps to identify sensitive area for future processes. This knowledge will be essential when higher demands and slimmer margins on light weight structures will tie functions for product development, production and quality/inspection tighter together. An example of this is illustrated with the findings on the MSA on fillet welds a-height gauge. When the processes are optimised for robust settings with low variations the requirements will automatic raise on the measurement systems, naturally, the problem grows when established measurement principles suddenly are out-dated. The variability in the measurement system needs to be ten times lower than the lack of precision of the process.

Conclusions

The above investigation shows that it is possible to improve the welding process performance by the use of parameter design without up grading the hard ware and tolerances, by doing so the pre-conditions for both product development and quality/inspection changes. Improved performance of the process can be used for further product improvements, but it will increase the demands on inspection equipment and inspection sampling and feed-back. Forms for increased interdisciplinary co-operation need to be visualised and developed.

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