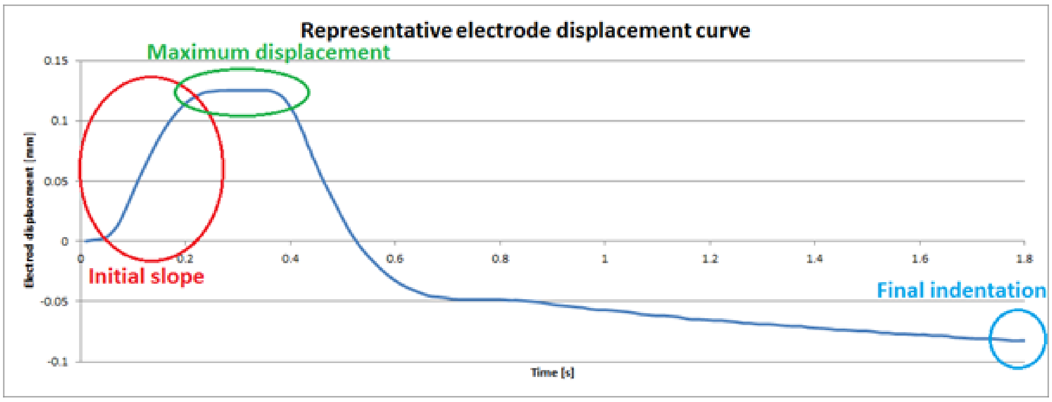
AWIC – Adaptive Welding indentation control



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VINNOVA Energimyndigheten TRAFIKVERKET FKG VOLVO SCANIA VOLVO

Table of contents

1 Summary

Denna förstudie har syftat till att mäta och utvärdera elektrodförskjutningen vid punktsvetsning som en metod att kvalitetssäkra en enskild punktsvets. Kvalitetssäkring har hög prioritet inom dagen fordonsindustri. Detta görs idag främst med hjälp av förstörande provning, fläkning. Delvis används även adaptiv styrning, där den dynamiska resistansen utgör grunden, för att säkerställa och mäta kvaliteten på var enskild svets. Resultaten från denna förstudie visar att elektrodförskjutningen i framtiden skulle kunna utgöra en viktig del i kvalitetssäkringen eftersom en stark korrelation mellan elektrodförskjutningen och svetskvaliteten har kunnat påvisas.

Punktsvetsning är den idag mest frekvent använda fogningsmetoden inom fordonsindustrin. En modern bil innehåller idag ca 6000 punktsvetsar. Metoden har uppnått hög popularitet inom fordonsindustrin tack vare att den är kostnadseffektiv, har god möjlighet att automatiseras och har hög åtkomlighet. Processen är också relativt robust, dock så vågar man inte lite på var och en av punkterna på grunda av stora kvalitetsvariationer, framför allt i plåtkombinationer innehållande mer avancerade material. Detta har lett till att man idag sätter flera extrapunkter i varje komponent för att säkerställa hållfastheten i varje produkt. Genom att mäta svetskvaliteten i varje punkt med hjälp av elektrodförskjutningen skulle således antalet svetsar i varje komponent kunna minskas och optimeras med avseende på kvaliteten på de övriga svetsarna.

I denna förstudie har ett antal, mer eller mindre, komplexa materialkombinationer testats och elektrodförskjutningen har mätts med två olika mättekniker, en extern laserförskjutningsmätare och med hjälp av en kraftsensor som är inbyggd i en befintlig servotång. Resultaten har visat på en korrelation mellan den maximala elektrodförskjutningen och pluggstorleken på svetsen. Pluggstorleken är ett vanligt sätt att mäta svetskvalitet för denna metod. Resultaten har också visat på korrelation mellan hastigheten i förskjutning, d.v.s. gradienten på förskjutningskurvan i den initiala fasen, och strömstyrkan. Dessa resultat påvisar att förskjutningskurvorna skulle kunna användas dels för att mäta kvaliteten på varje svets, dels för att prediktera risken för sprut. Deltagande företag har visat stort intresse för resultaten och dess möjlighet till enklare kontroll och förbättrad svetskvalitet.

2 Executive summary

The purpose of this pre-study was to measure the electrode displacement during resistance spot welding (RSW) and to investigate if these measurements can be used as a parameter for the quality assurance. The quality assurance today is mainly performed with destructive testing, which is a highly time consuming process. The possibility to use of the electrode displacement as a quality indicator would enable a non-destructive in-line method, which would decrease the testing time significantly.

The RSW-process is today a relatively robust process. However, the quality is not fully consistent between welds and therefore extra redundant spots are often welded in each product in order to assure the component quality. The use of the electrode displacement as an on-line quality measurement could therefore also enable the possibility to optimize and reduce the number of welds in each component. This would in turn decrease the process time for every component in an industry where every millisecond counts.

This study is based on the hypothesis that the electrode position is continuously changed during the RSW-process, mainly due to the thermal expansion in the sheet material. The hypothesis was evaluated initially in the pre-study, and was found to be principally true.

The results from this study show a correlation between the maximum electrode displacement during the welding process cycle and the weld quality, measured by the nugget size from peel testing. This correlation implies that the electrode displacement can be used as a quality indicator for the weld, which would increase the safety of each product and decrease both the testing time and the process time. It is also shown in the results that a good correlation can be seen between the gradient in the initial part of the displacement curve and the current level. It is possible that this correlation could be used to prevent spattering by implementation of an adaptive algorithm controlled by the slope of the displacement curve.

In short, this pre-study has shown possibilities for using the electrode displacement as a weld quality indicator. It could also be used in adaptive algorithms to indicate risk for, and avoid, weld spatter. The participating companies

have shown a great interest in the results and the possibility to use the electrode displacement method to simplify and improve the weld quality.

3 Background and aim

Resistance spot welding (RSW) is the dominant joining technology in the transportation industry. A modern vehicle today contains of approximately 6000 spot welds. The method is ideal in the automotive industry due to its low cost, high ability for automatization, high accessibility etc. The RSW process is also relatively robust for conventional materials. However, since the quality of each spot weld cannot fully be trusted, several extra welds are often done in order to secure the product quality. The quality is increasingly important when the materials get thinner, mixed and more advanced; meanwhile the quality assurance becomes more and more difficult. The aim of this project was to evaluate a new method for quality insurance of spot welds based on measuring the electrode displacement during the welding process[1].

A number of different methods for quality assurance in RSW have been developed since its invention. The Cambridge Weld Institute[2] used the temperature of the spot weld as a quality parameter, Rokhlin and Adler[3] used Ultrasonic waves and Gedeon[4] used the dynamic resistance in the circuit in order to evaluate the spot weld quality. However, none of these techniques have been proved to fully assure the quality of the welds, since none of them have been able to either predict the strength of the weld as well as prevent spattering[5][6]. Improved quality assurance would make it possible to decide whether the next spot weld is needed or not and thereby optimize the number of welds in each component and decrease the process time substantially in an industry where every millisecond counts.

A number of studies have been performed regarding electrode displacement as a quality measurement of the spot weld. These studies demonstrate the relationship between electrode displacements and weld quality, where the weld quality is defined by both nugget size and risk for spattering. An example of this relationship can be seen in *Figure 1*. The displacement of the electrodes derives mainly from the thermal expansion of the sheet material. However, an additional volume change due to phase transformation in the material is also reported to affect the displacement. The displacement is also affected by the plastic deformation of the material due to the electrode force. The increased temperature in the material decreases the tensile strength which in turn increases the plastic deformation. The total displacement is a summation of all these factors, where the thermal expansion and the phase transformation increases the sheet material volume, forces the electrodes apart and contributes with a positive value for the electrode displacement, while the plastic deformation decreases the distance between the electrodes and hereby contributes with a negative value for the electrode displacement[7][8][9].

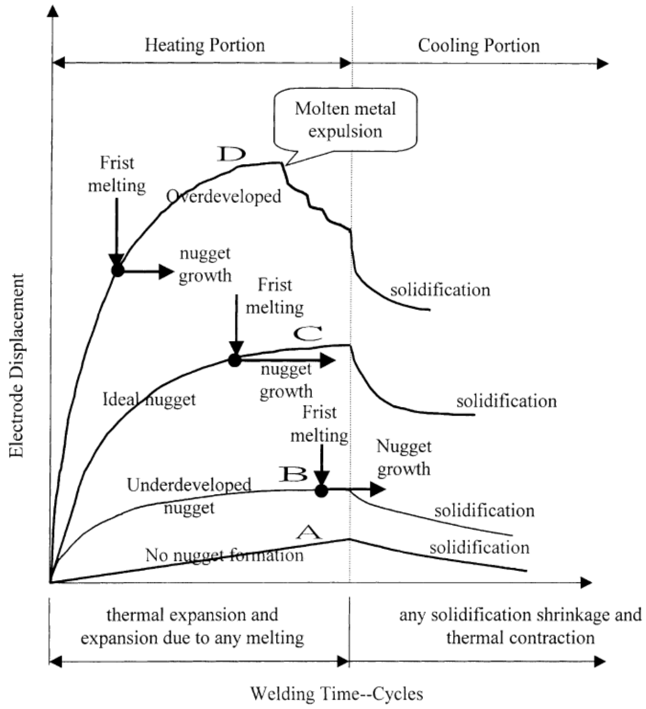


Figure 1. Illustration of relationship between electrode displacement and nugget growth[7].

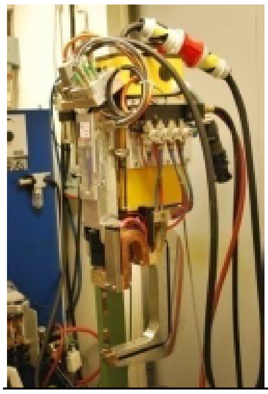
However, these earlier studies are all performed with rather simple material combinations, symmetric 0,7-1 mm thick 2T-combinations of uncoated low carbon steels, and have not investigated the possibility to use the electrode displacement as a quality measurement when welding advanced high strength steels or ultra high strength steels and multi-sheet combinations. In order to implement the displacement as a quality measurement in the automotive industry an investigation of the behaviour of different types of steel material needs to be performed. These studies are based on the use of external systems for the measuring. In order to secure the quality, by adaptive control, it is highly important that the measuring system is included in the existing equipment. Therefore this project was aimed at evaluating how the displacement of the electrodes behave for a number of different types of sheet combinations with different material properties and surface coatings as well as investigating if it is possible to: use the measurements for quality measurement, as a tool in the process optimization or as an adaptive control system.

4 Method

The experiments in this study were performed at Swerea KIMAB with the equipment presented in *Figure 2* - *Figure 4*. The equipment presented in *Figure 3* have a built in force sensor in the servo gun, which regulates the electrode position in order to maintain the force during the process and provides data for the displacement continuously during the welding process. The results from the external displacement sensor have been compared to the results from the equipment in *Figure 3*.

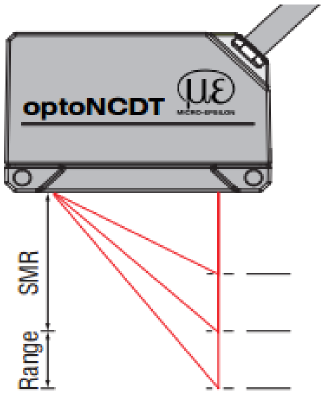
Max electrode force: [kN] (daN)	7
Short circuit current: [kA]	
Throat depth: [mm]	355
Current type: [AC, MFDC]	MFDC (1000Hz)
Water cooling per electrode [l/min]	4
Weld control unit:	PC-based BOS6000
Transformer:	
Inverter	Bosch 6000PSI
Welding gun]	Manual pneumatic ABB GWT-X gun

Figure 2. Resistance spot welding equipment from Bosch and ABB.



Max electrode force: [kN] (daN)	8
Short circuit current: [kA]	38
Throat depth: [mm]	
Current type: [AC, MFDC]	MFDC
Water cooling per electrode [l/min]	4
Weld control unit:	PC-based Matuschek Servo studio
Transformer:	Expert 222kVA(4diod) 50 turn ratio
Inverter	Matuschek Servo SPATZ M800LL
Welding gun	Matuschek Servo gun C-type

Figure 3. Resistance spot welding equipment from Matuschek, with built in displacement measurement system.



Measuring range	10 mm
Start of measuring range	20 mm
Linearity	8-10 µm
Repeatability	0,5 µm
Measuring rate	4 kHz

Figure 4. External distance measuring equipment used for the experiments.

The set-up for the external measurements can be seen in *Figure 5*. The laser sensor is placed onto the lower electrode and a measuring plate is placed onto the upper electrode. The distance between the sensor and the plate is measured continuously during the whole process, from the start of squeeze time to the end of the hold time. The distance between the sensor and the measuring plate was found to be constant during the squeeze time, and therefore this position was used as the zero point in the measurements.

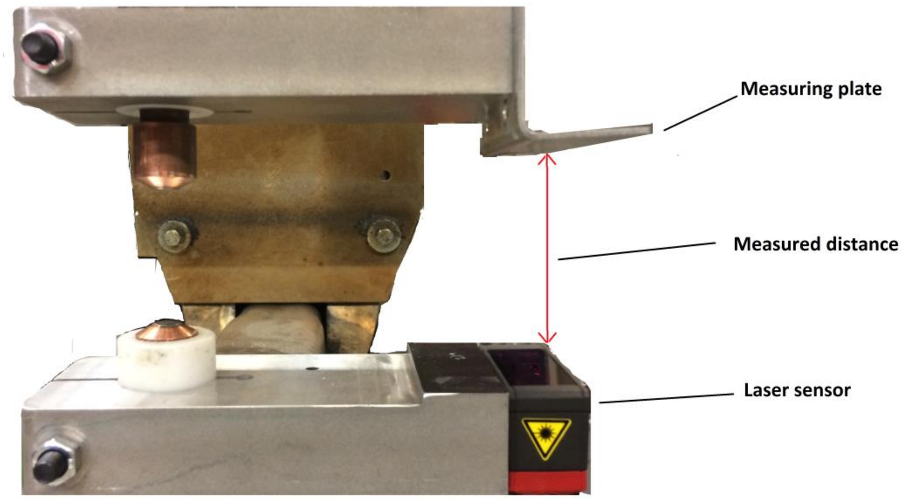


Figure 5. Set-up for the experiments performed at Swerea KIMAB.

5 Experiments

The test matrix for the experimental part of the project can be seen in Table 1.

Table 1. Test matrix for experimental part of the project.

Experiment ID	1	2	3	4
Material 1	DP600	DC05	Usibor1500P	DP600
Coating	Z100	Uncoated	AS150	Z100
t [mm]	1,5	1,0	1,2	1,0
Material 2	DP800	DC05	Usibor1500P	DP600
Coating	Z100	Uncoated	AS150	Z100
t [mm]	1,5	1,0	1,2	1,2
Material 3	-	-	-	DC04
Coating	-	-	-	Z100
t [mm]	-	-	-	0,65

Experiment 1, 4 and 5 have been evaluated by peel testing of the welded specimens and then comparing the maximum displacement to the nugget size. These specimens were produced with varied current levels in order to examine the influence of the current. Experiment 3 was evaluated by cross-section analysis of the welds and comparing the maximum displacement to the weld geometry. These specimens were produced with varied weld time in order to examine its influence.

The basic idea with the setup of the test matrix was to first evaluate more simple combinations containing of two sheets with similar thicknesses and material properties. Experiment 1, 2 and 3 can be seen as such combinations. Experiment 4 was performed in order to evaluate the behaviour in ultra high strength steels, since this is both more difficult to weld and a type of material which is gaining more popularity in the automotive industry. Experiment 5 was performed in order to evaluate this method for multi-sheet combinations.

5.1 Process parameters for experiments

The process parameters for each experiment are presented in Table 2-

Table 5 below.

Table 2. Process parameters for experiment 1.

Force	Weld time	Weld current	Hold time
4 kN	320 ms	Varied (5,3-8,6 kA)	2000 ms

Table 3. Process parameters for experiment 2.

Force	Weld time	Weld current	Hold time
2,9 kN	Varied (10-430 ms)	8,0 kA	2000 ms

Table 4. Process parameters for experiment 3.

Force	Weld time pre-pulse	Weld current pre-pulse	Pause time	Weld time main pulse	Weld current main pulse	Hold time
4,0 kN	100 ms	4,0 kA	40 ms	310 ms	6,0-7,5 kA	2000 ms

Table 5. Process parameters for experiment 4.

Force	Weld time pre-pulse	Weld current pre-pulse	Weld time main pulse	Weld current main pulse	Hold time
3,1 kN	40 ms	10,0 kA	300 ms	6,4-9,7 kA	2000 ms

6 Results

6.1 Experiment 1

This experiment was performed both on the equipment presented in *Figure 2* and *Figure 3*. The results from the experiments are presented in *Figure 6* and *Figure 7*.

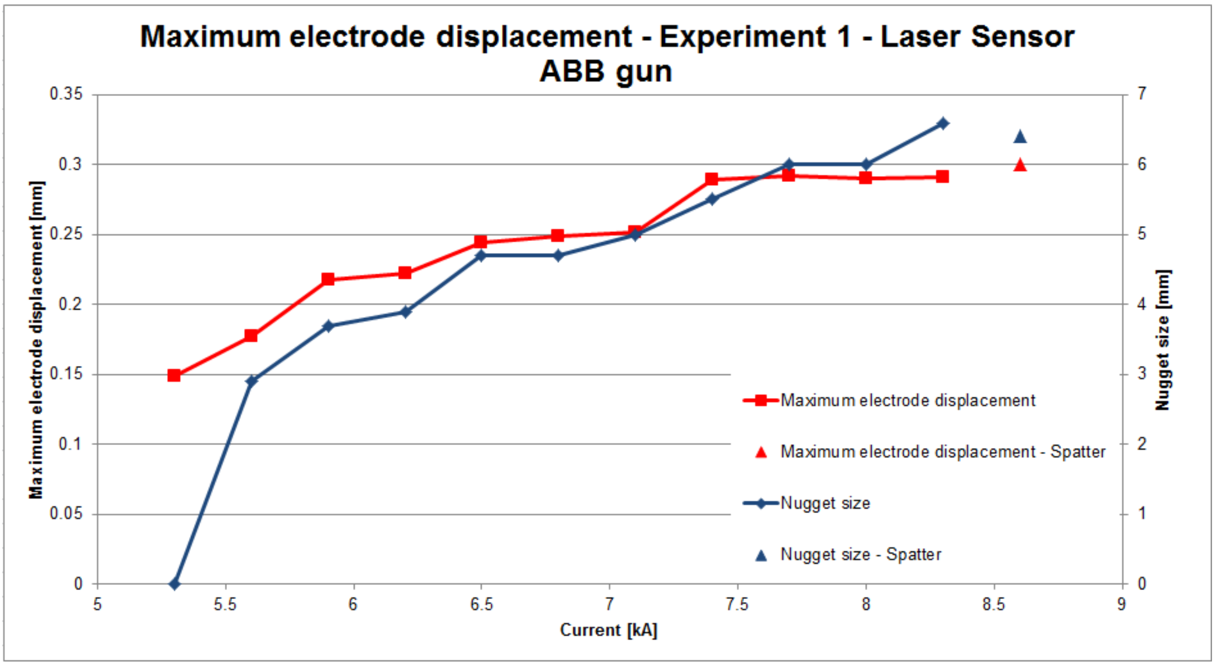


Figure 6. Electrode displacement and nugget size as function of current level for experiment 1. Welds performed at ABB gun and with the laser sensor.

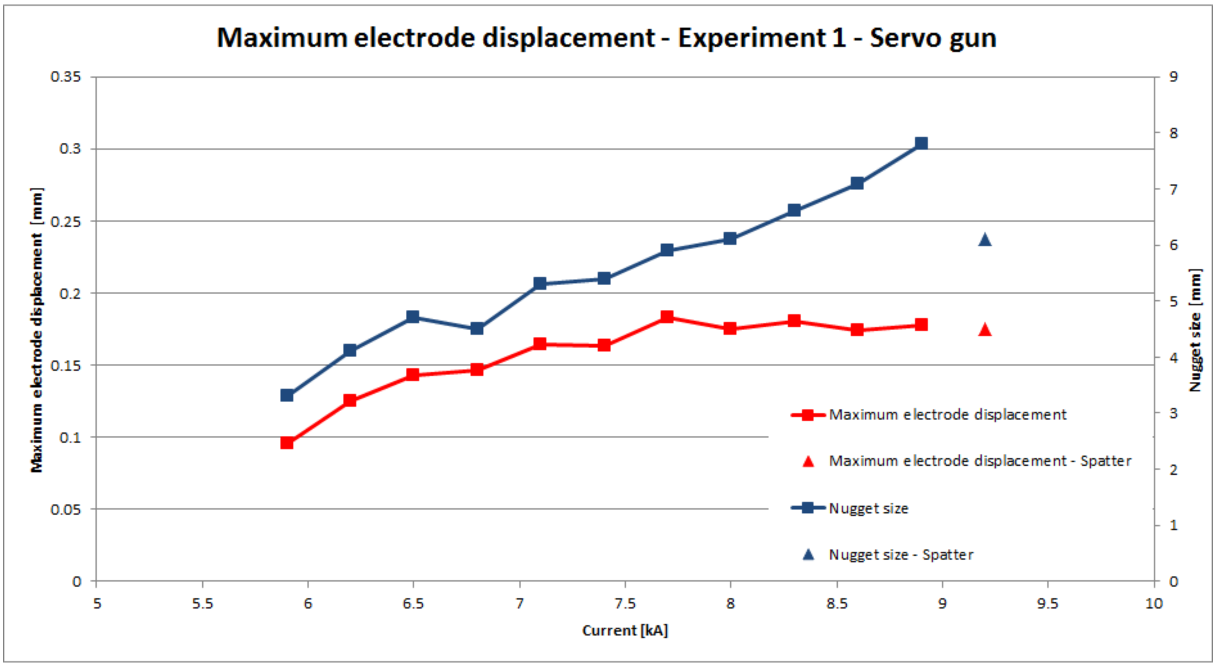


Figure 7. Electrode displacement and nugget size as function of current level. Welds and displacement measurements performed with Matuschek servo gun

The Displacement curves for the two trials are presented in *Figure 8* and *Figure 9*. *Figure 10* shows the gradient during the initial part of the displacement curves for six different current levels. *Figure 11* shows the correlation between the gradient of the initial part of the displacement cure and the current level.

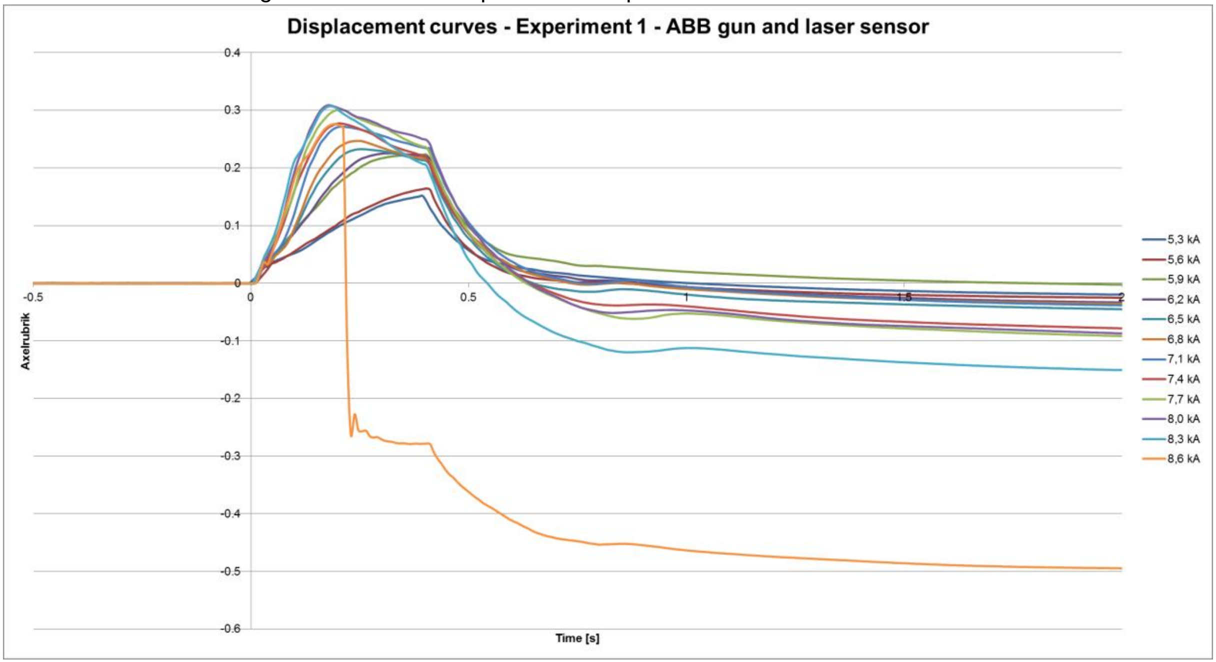


Figure 8. Displacement curves from experiment 1, performed with ABB gun and laser sensor.

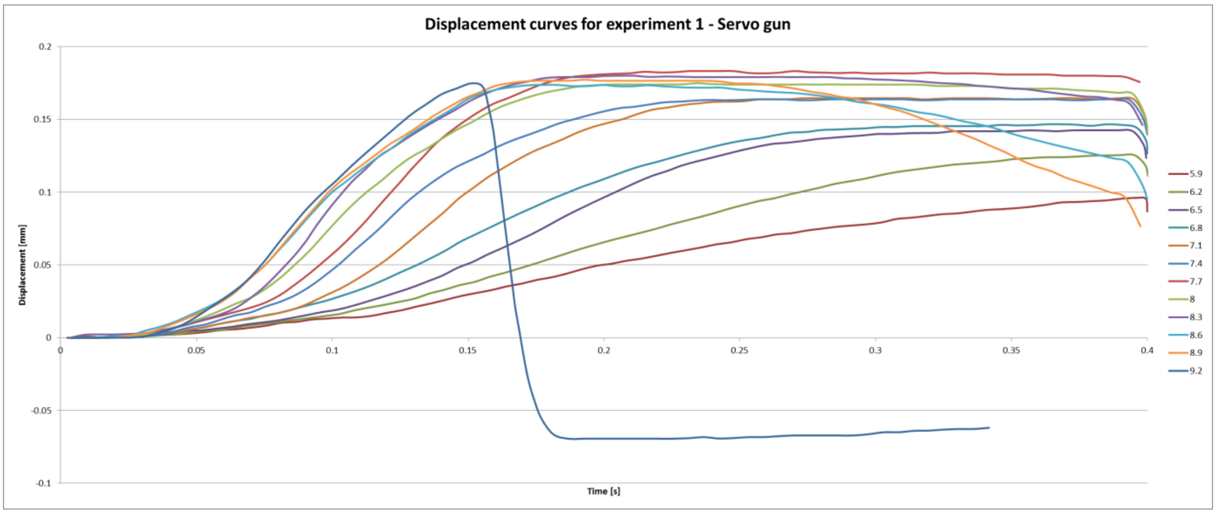


Figure 9. Displacement curves from experiment 1, performed with Matuschek servo gun.

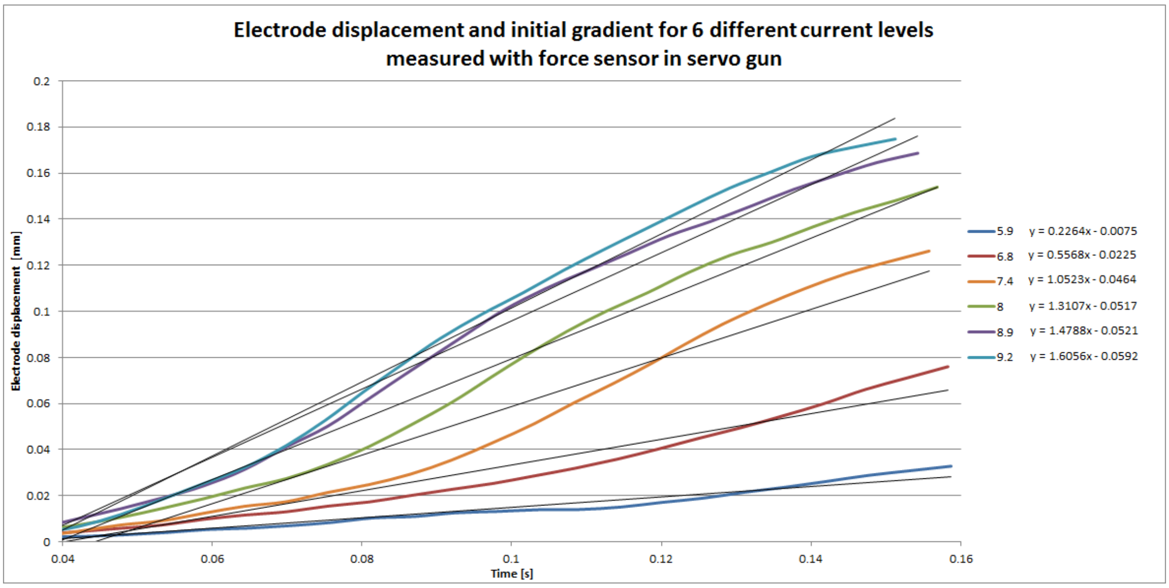


Figure 10. Gradient during the initial part of the displacement curves for six different current levels.

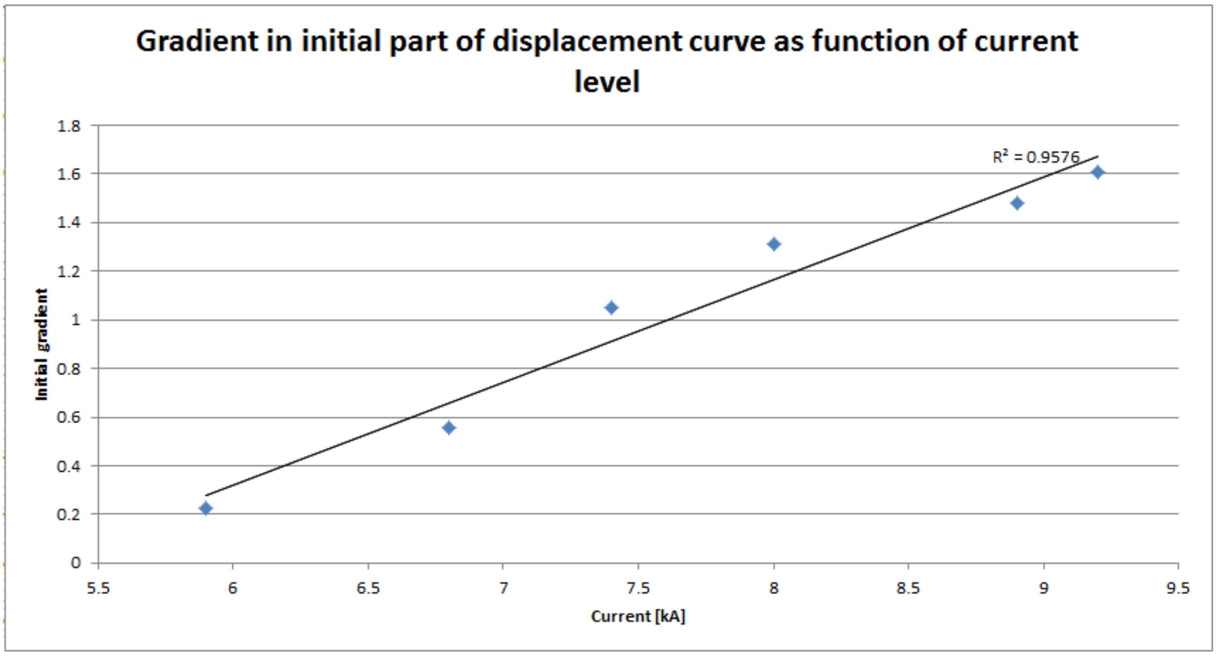


Figure 11. Correlation diagram for gradient of initial part of displacement curve and current level.

6.2 Experiment 2

This experiment was performed on the ABB gun. The maximum electrode displacement, final lens height and final lens width is presented as function of weld time in *Figure 12*.

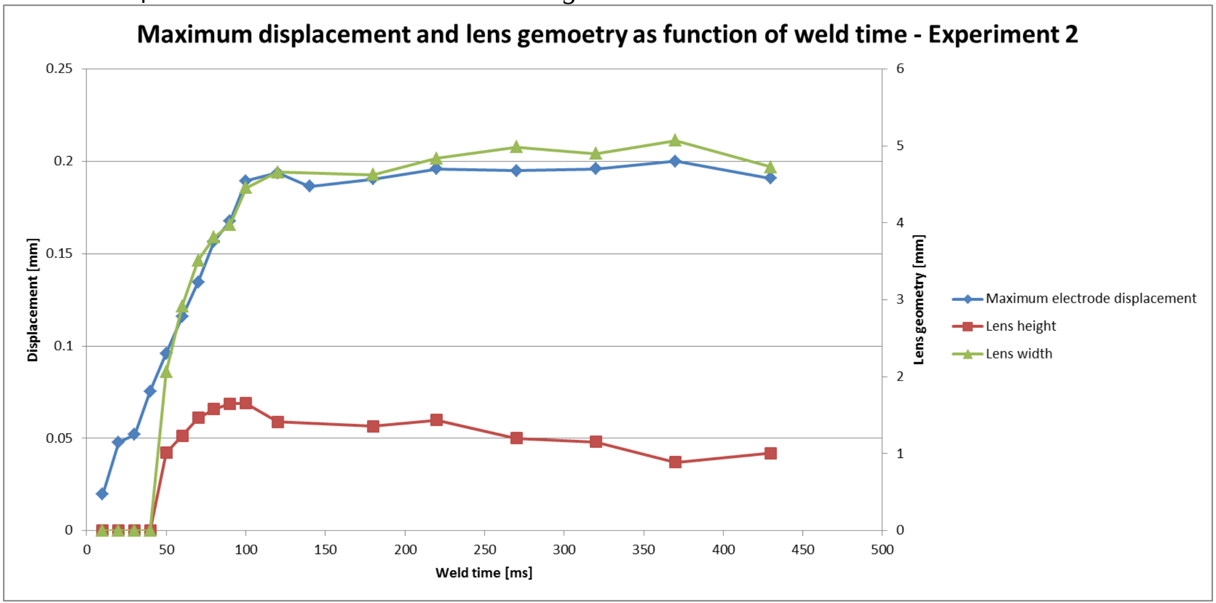


Figure 12. Maximum electrode displacement, final lens height and final lens width as function of weld time for experiment 2.

The electrode movement for the different weld times can be seen in *Figure 13*. *Figure 14* shows the electrode displacement during the first 500 ms of the weld cycle during experiment 3.

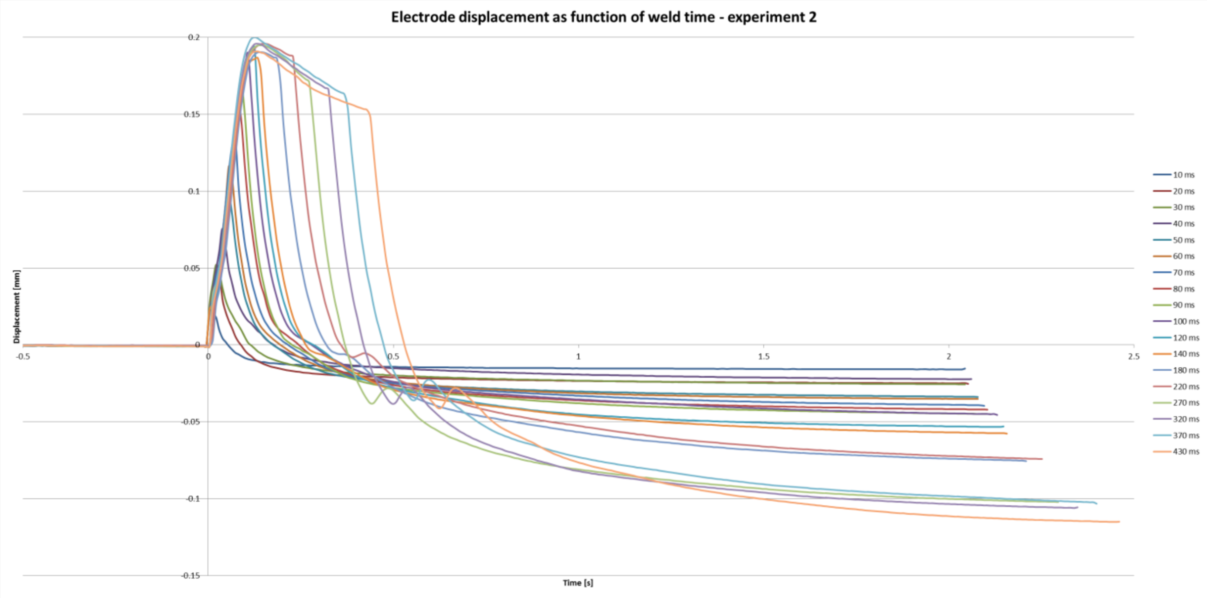


Figure 13. Continuous electrode movement from experiment 2, experiment performed with ABB gun and laser sensor.

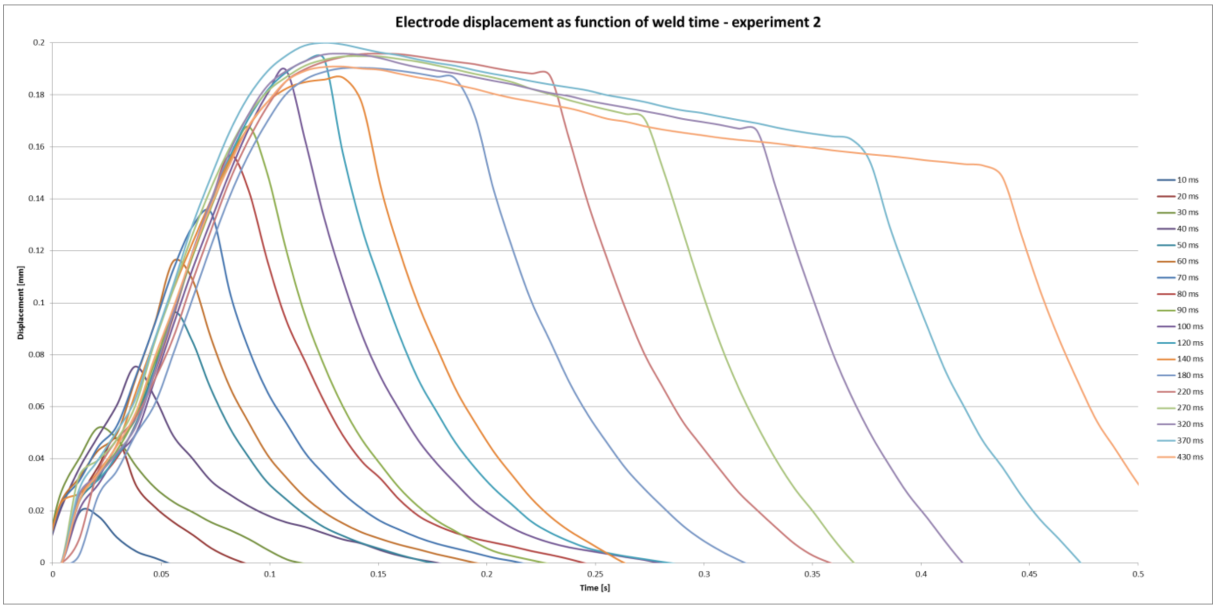


Figure 14. Electrode movement during first 500 ms of weld cycle from experiment 2.

6.3 Experiment 3

This experiment was performed with the Matuschek servo gun. The displacement was measured with both the laser sensor and the Matuschek equipment. The maximum electrode displacement and nugget size as function of current can be seen in *Figure 15*. *Figure 16* shows the correlation between the two measuring methods.

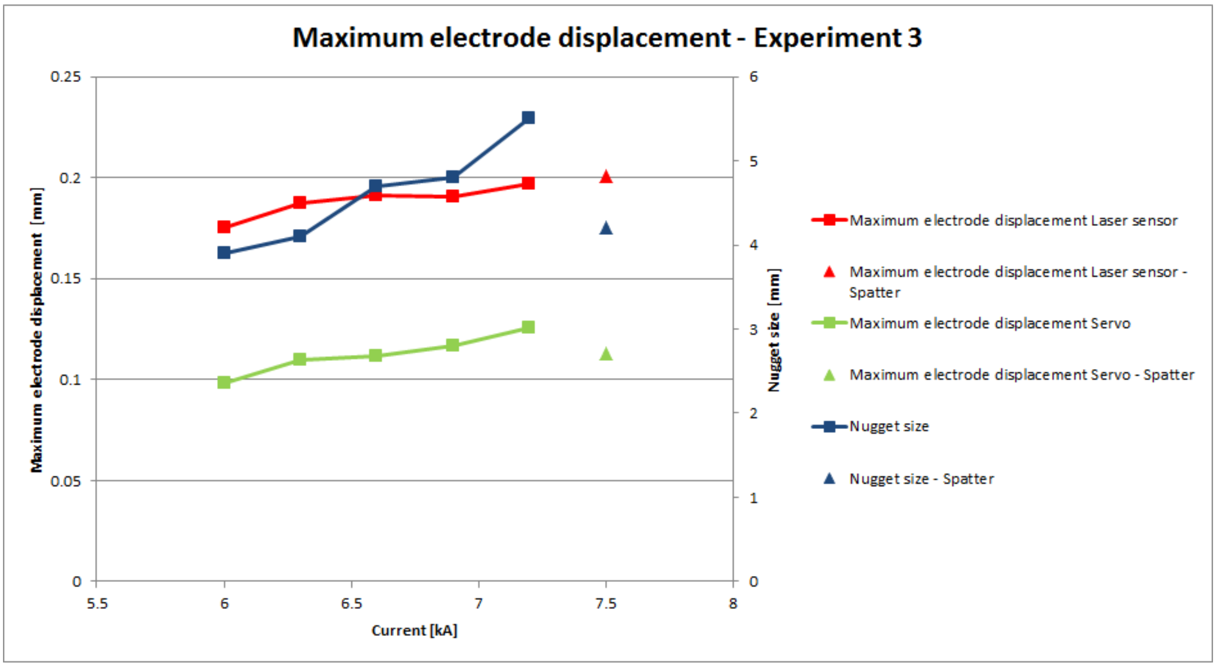


Figure 15. Maximum electrode displacement and nugget size as function of current level, experiment 3.

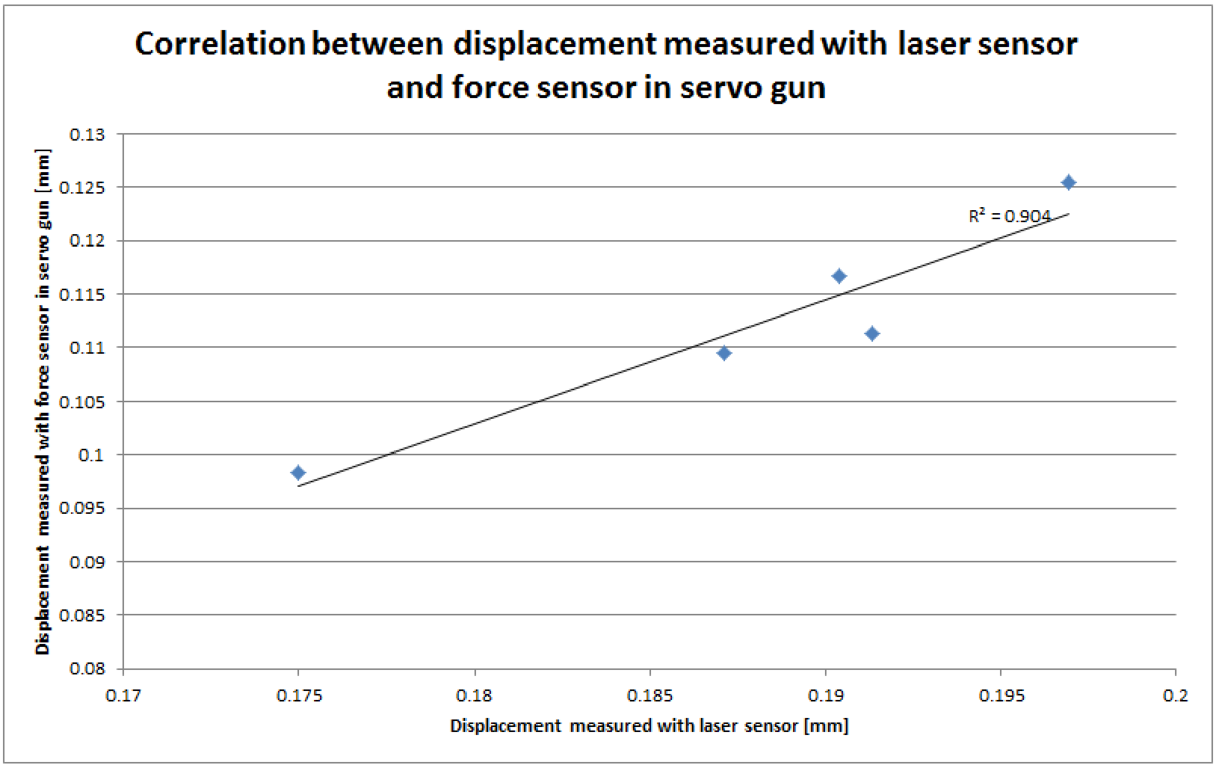


Figure 16. Correlation between electrode displacement measured with laser sensor and with force sensor in servo gun.

The continuous electrode movement for the different current levels can be seen in *Figure 17*, measured with laser sensor, and *Figure 18*, measured with Matuschek servo. *Figure 19* and *Figure 20* shows the electrode displacement during the first 400 ms of the process.

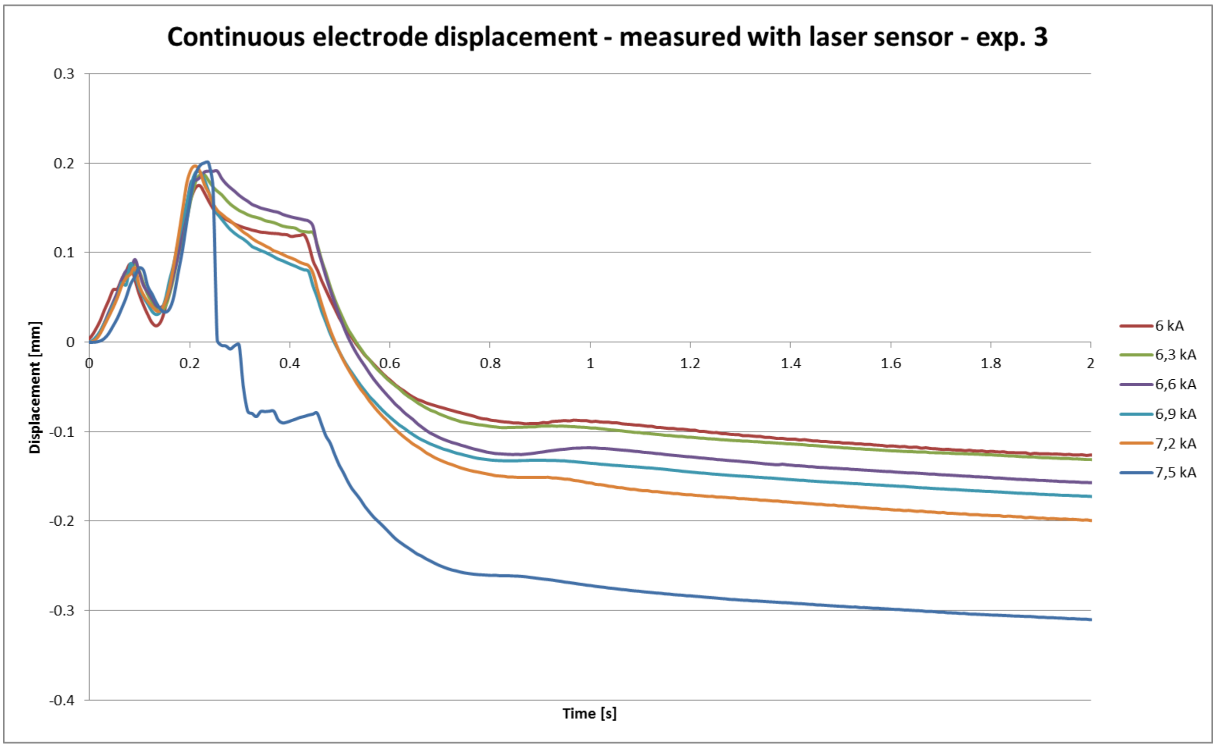


Figure 17. Continuous electrode displacement from experiment 3. Measured with laser sensor.

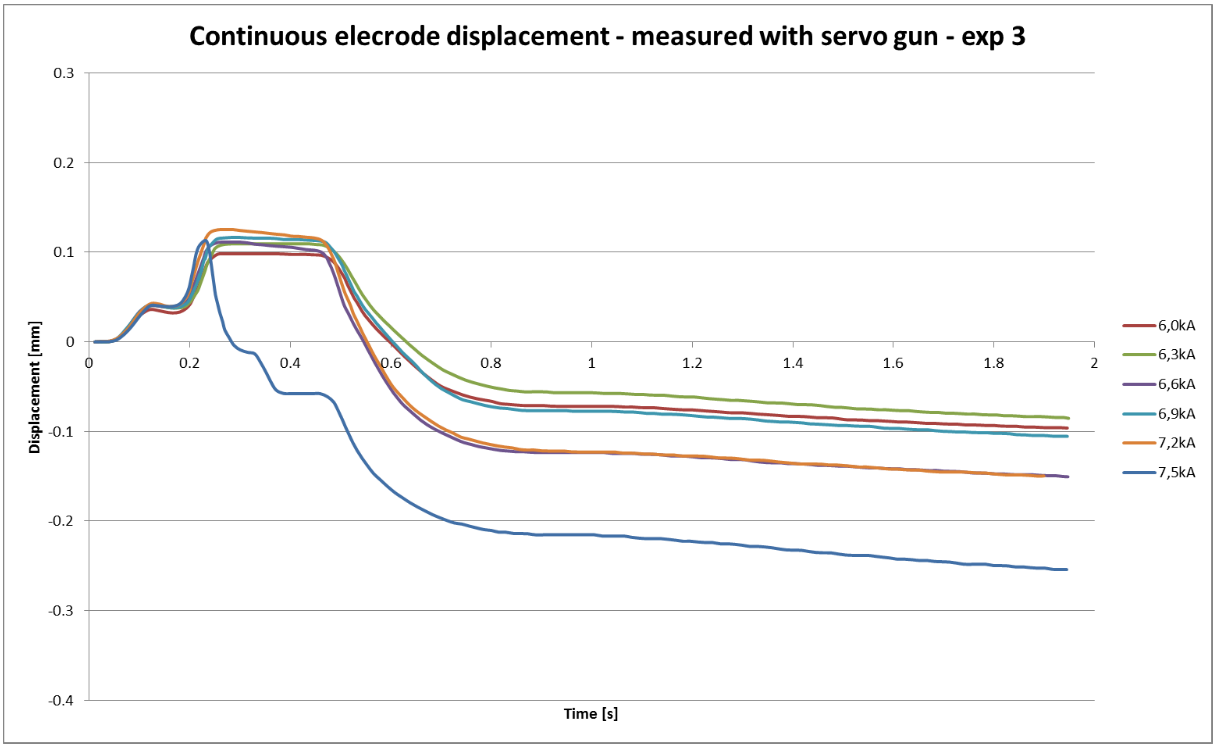


Figure 18. Continuous electrode displacement from experiment 3. Measured with servo.

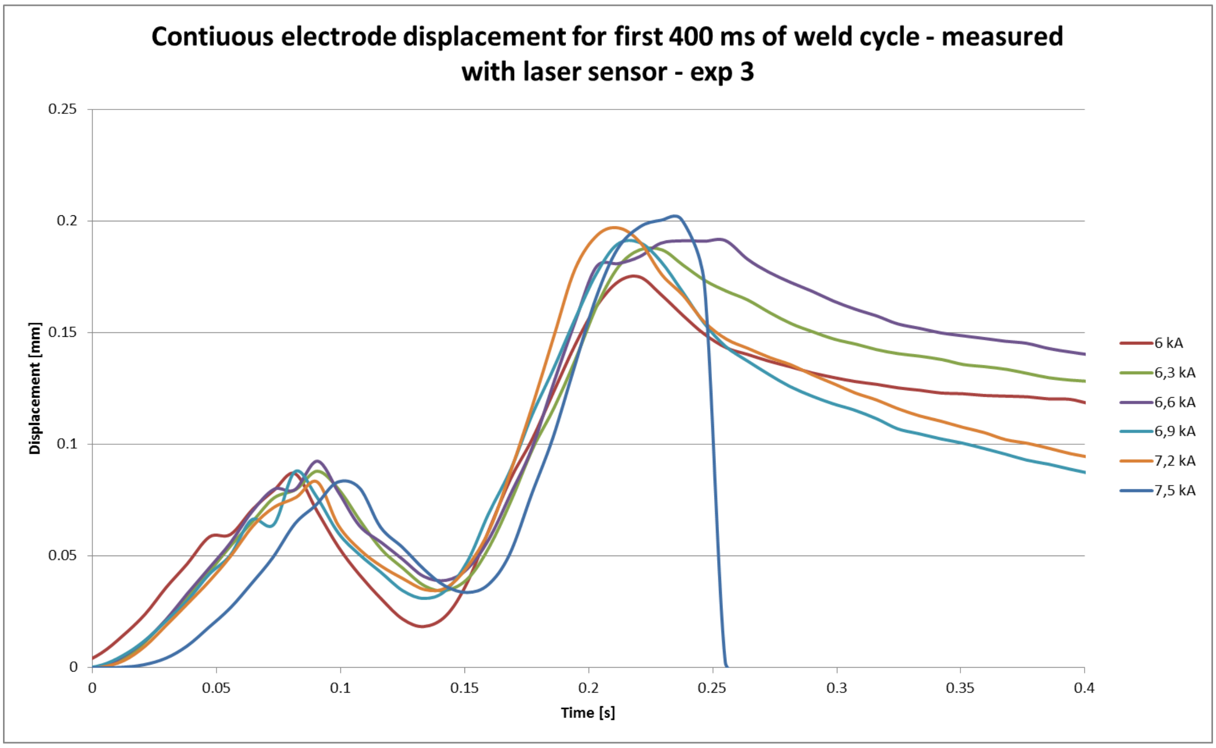


Figure 19. Continuous electrode displacement during first 400 ms of experiment 3. Measured with laser sensor.

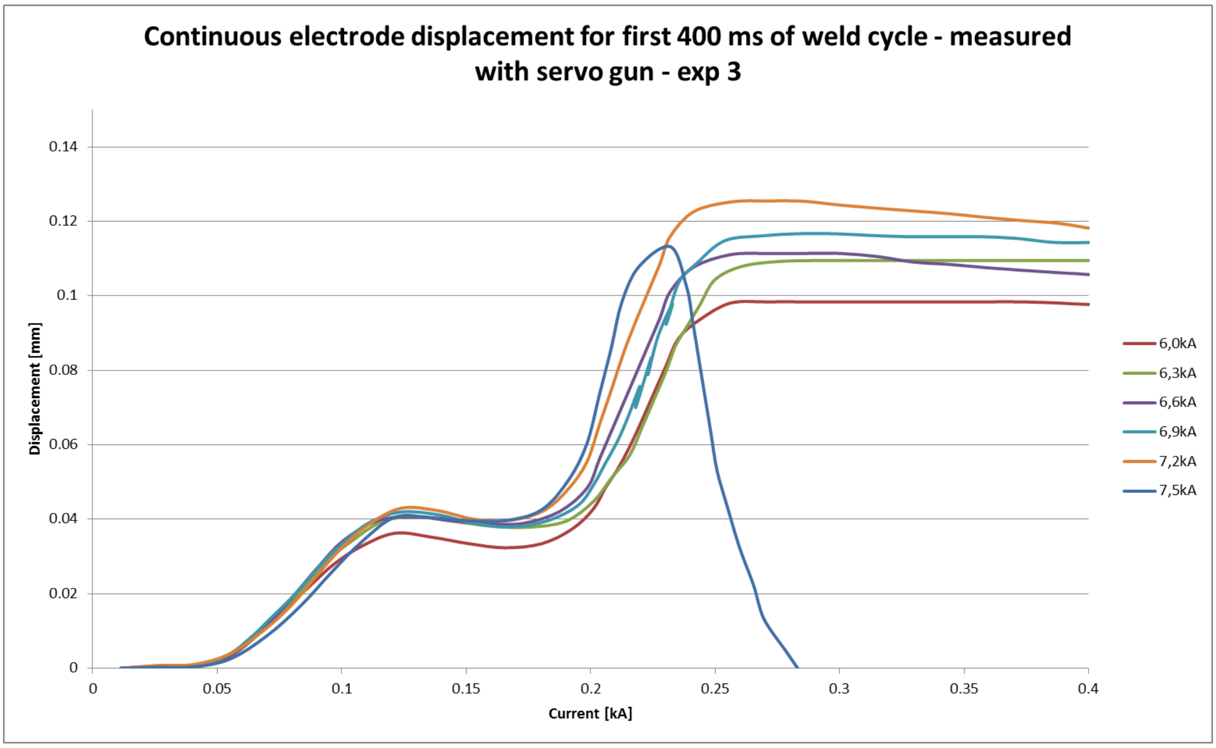


Figure 20. Continuous electrode displacement during first 400 ms of experiment 3. Measured with servo.

6.4 Experiment 4

This experiment was performed with the Matuschek servo gun. The displacement was measured with both the laser sensor and the Matuschek equipment. The maximum electrode displacement and nugget size can be seen as function of weld current in *Figure 21*.

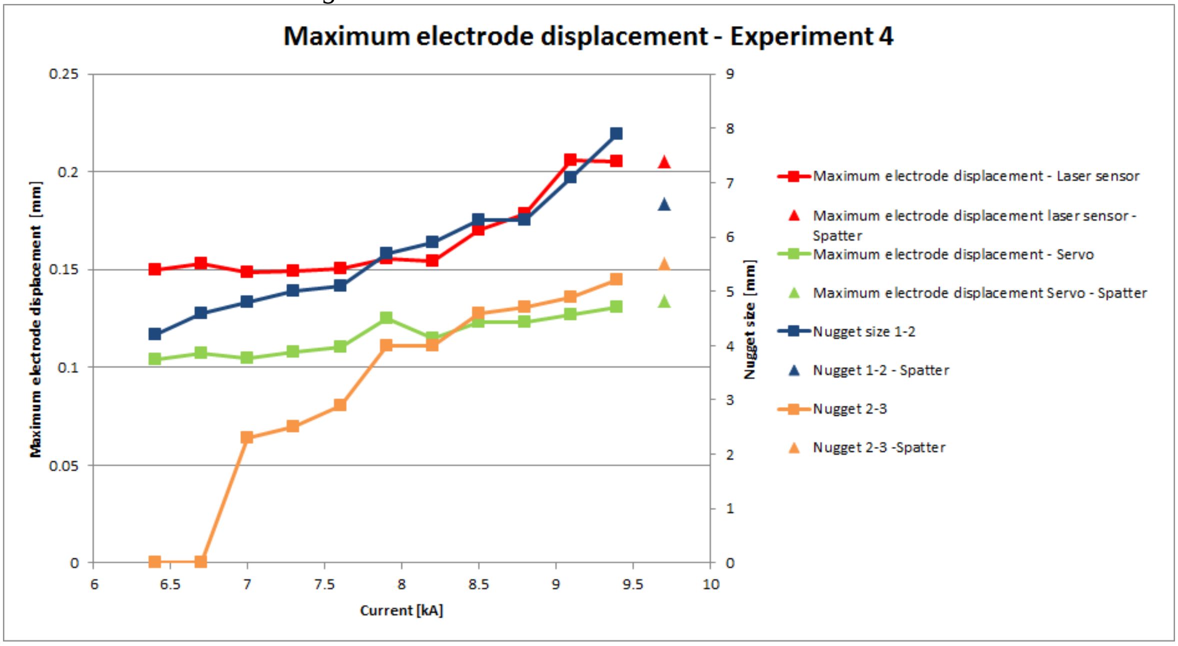


Figure 21. Maximum displacement and nugget size as function of weld current, experiment 4.

The continuous electrode movement during the process can be seen in*Figure 22*, measured with laser sensor, and *Figure 23*, measured with servo. *Figure 24* and *Figure 25* shows the electrode displacement during the first 400 ms of the weld cycle. *Figure 26* shows the electrode displacement for the six highest current levels between 100 and 400 ms into the process.

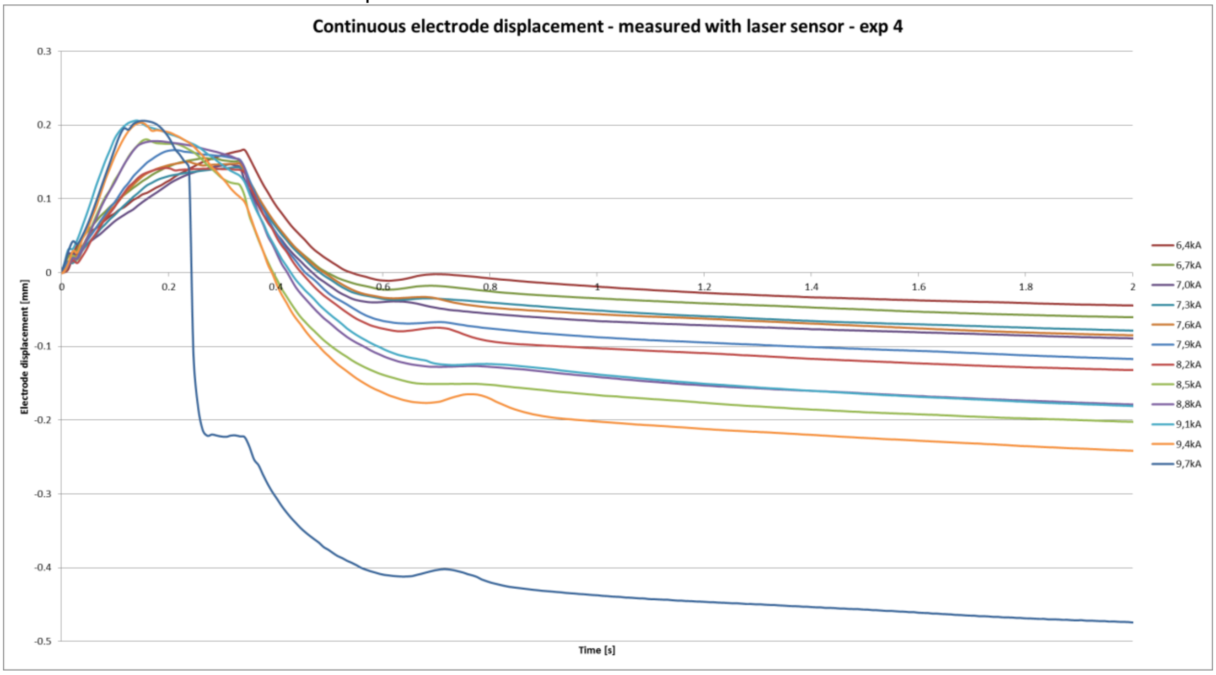


Figure 22. Continuous electrode displacement from experiment 4. Measured with laser sensor.

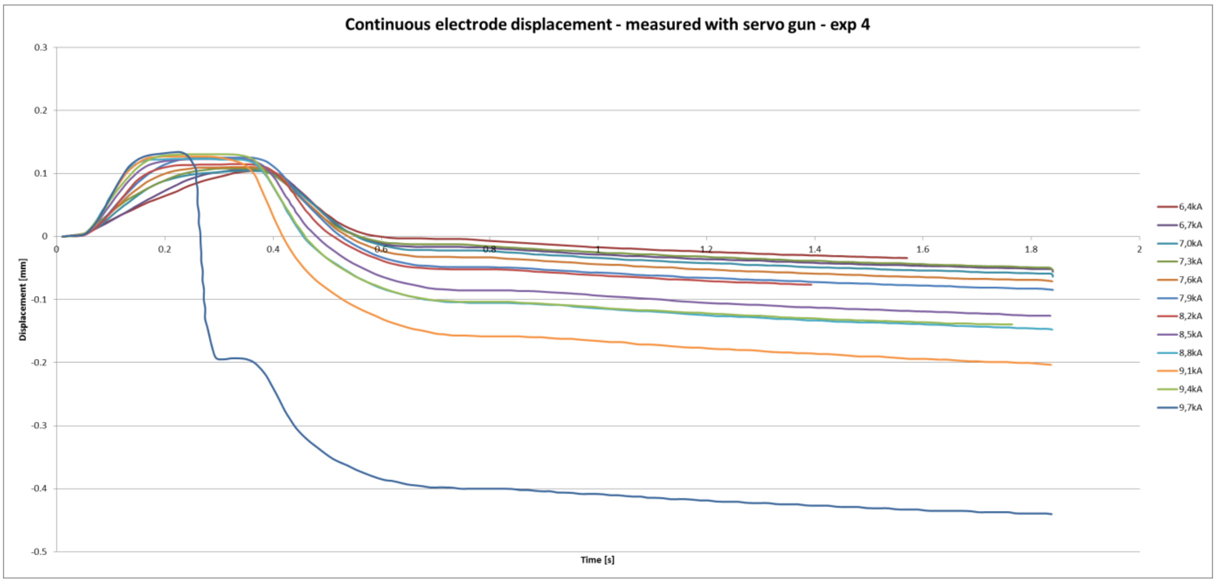


Figure 23. Continuous electrode displacement from experiment 4. Measured with servo.

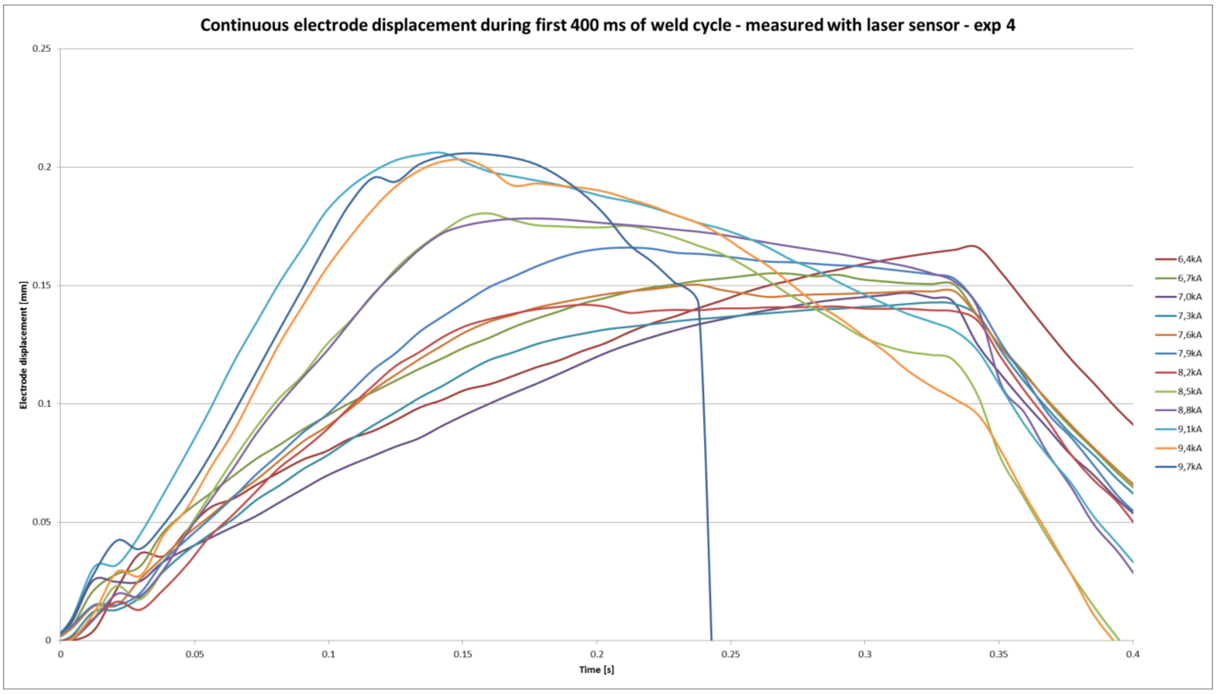


Figure 24. Continuous electrode displacement during first 400 ms of welding cycle for experiment 4. Measured with laser sensor.

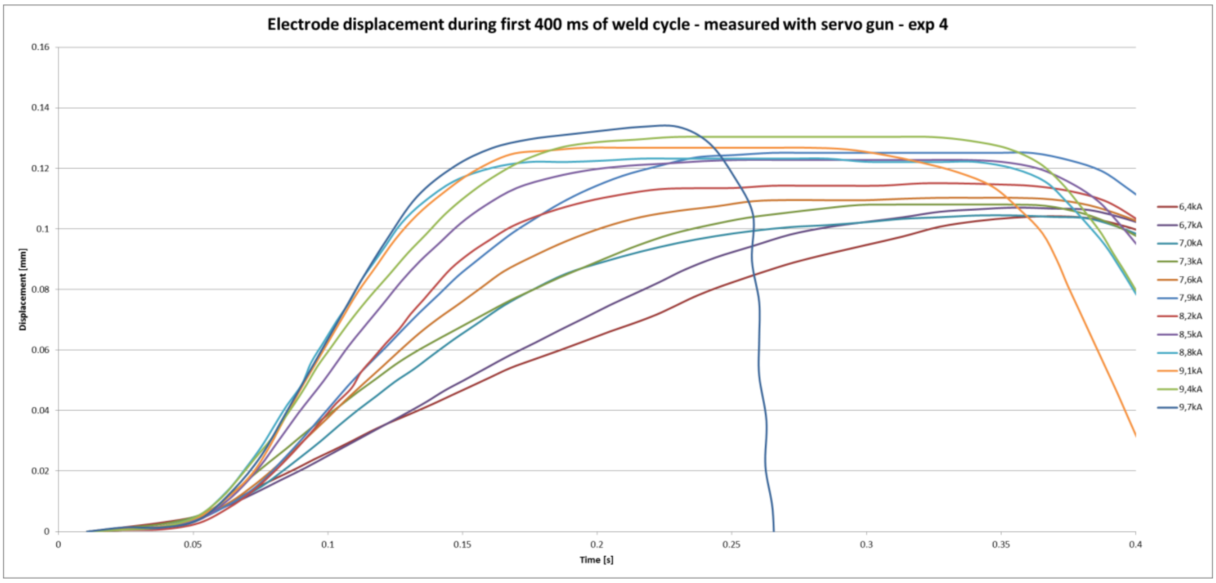


Figure 25. Continuous electrode displacement during first 400 ms of welding cycle for experiment 4. Measured with servo gun.

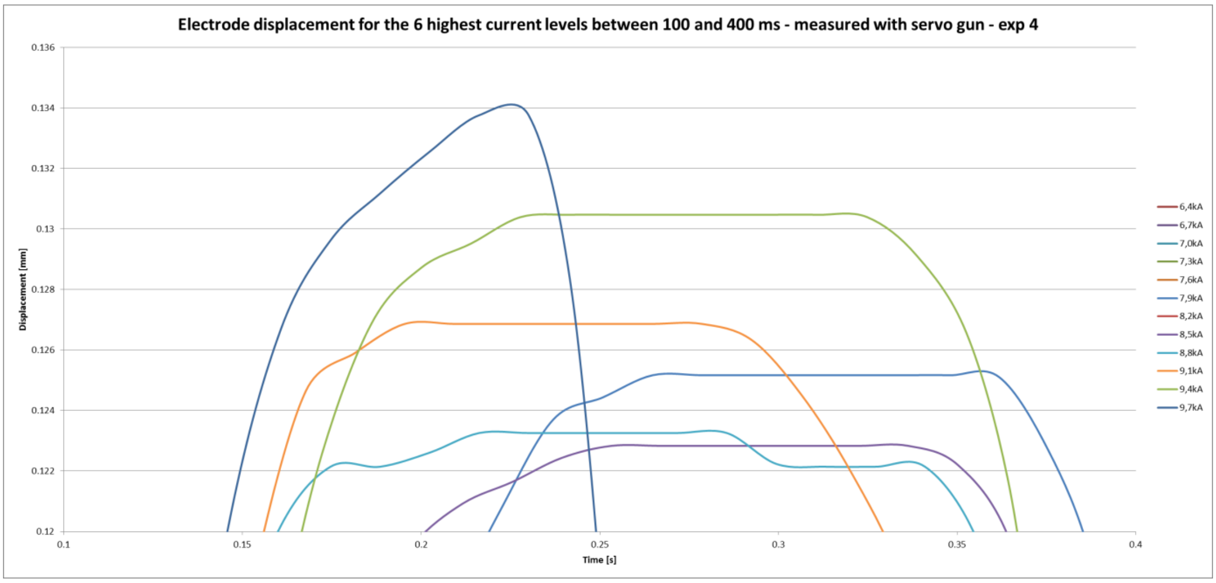


Figure 26. Electrode displacement for the 6 highest current levels between 100 and 400 ms into the process of experiment 4. Measured with servo gun.

7 Dissemination and publications

7.1 Knowledge and result dissemination

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	A full project is planned
Föras vidare till produktutvecklingsprojekt	X	After finished full project
Introduceras på marknaden	X	After finished full project
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

7.2 Publications

No external publications have been produced within the pre-study

8 Discussion

The main goal with this project was to investigate if the electrode displacement could be used in order to improve the quality in the RSW process in the automotive industry. The study is based on the hypothesis that the electrode position is continuously changed during the welding process mainly due to the thermal expansion and contraction in the sheets. The measurements in this study was performed with two different equipment, one external laser distance sensor which was mounted on the electrode arms, and one displacement signal from a servo gun from Matuschek with a built-in force sensor. The results from the experiments, the industrial interest, the requirements for implementation in industrial applications and future work are discussed in this chapter.

When comparing the continuous electrode movement two main differences can be seen between the measurements performed with the laser sensor compared to the measurements performed with the Matuschek servo gun. The two main differences between the measuring methods are the amplitude of the curve and the initial shape of the curve. The measurement performed with the laser sensor shows larger amplitude and a larger maximum displacement for all the trials. This is assumed to derive from the flexibility in the gun arms, which cannot be compensated for with the force sensor in the servo gun. The measurements performed with the laser sensor shows a large initial gradient from the start of the process, while the measurements performed with the servo gun shows a small gradient during the first part of the process and a larger gradient approximately 50 ms into the process. This is also assumed to be caused by the flexibility in the arms and the fact that the servo measurements are not able to take the flexibility into account.

The different experiments all show similar displacement curves, regardless of material combination. The displacement curve can be divided into three parts, illustrated in *Figure 27*. The three most interesting parts are the initial slope of the curve during the thermal expansion of the weld, the maximum displacement and the final indentation.

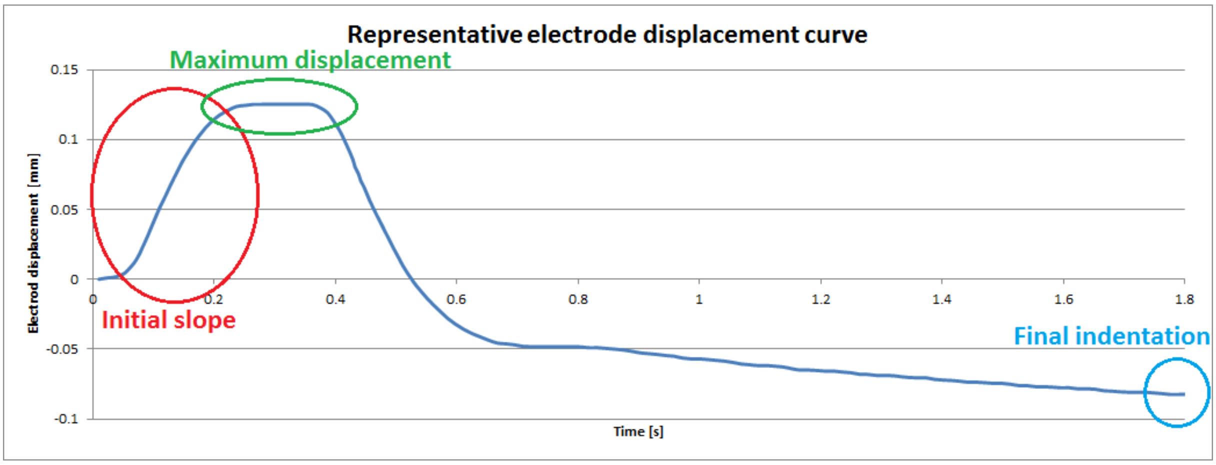


Figure 27. Illustration of three parts of the displacement curve, which are of main interest.

It can be seen in the results from the experiments performed with varied current level that the slope in the initial part of the curve increases with increasing current level. This phenomenon can for example be seen in *Figure 10* and *Figure 11*. As a comparison it can be seen in *Figure 14* that the slope of the curve does not change significantly during the experiments were the weld time is varied and the current is kept constant. The increase in slope is thought to originate from the fact the increased current leads to an increase in developed heat which in turn increases the thermal expansion. Every material combination seems to have a range of the slope where a required weld quality is achieved. The initial slope of the curve is also found to be the best indication for the risk for spatter; therefore this part of the curve might be able to serve as an input to an adaptive control system. A development of a system which combines the today used dynamic resistance with the information from the electrode displacement could probably increase the capability to obtain a higher quality of the welds and decrease the number of spattered welds.

The results from the experiments do also show that the maximum displacement coincides with the nugget size. As shown in *Figure 6*, *Figure 7* and *Figure 15* both the maximum electrode displacement and the nugget size increases with increasing current level. These results imply that the electrode displacement curve is definitely a possible quality indicator. The maximum displacement can be used both as a measurement of the weld quality in production and as a tool in the process parameter optimization.

The maximum displacement can possibly be used in a quality monitoring system in production. This would enable the opportunity for an on-line decision of where the next weld needs to be placed, dependant on the quality of the previous weld, in order to achieve the required quality. This in turn would lead to an optimized number of welds in every component. The use of the maximum displacement during the process parameter optimization can possibly be combined with, or even replace, the peel testing of each parameter set-up and decrease the time for this process.

Experiment 4 was performed in order to investigate how the electrode displacement behaves during welding of a combination where a joint is produced in more than one interface. *Figure 26* shows that a second increase in the displacement takes place after the planarization of the displacement curve. This can be seen approximately 250 ms into the process in this case. It is possible to assume that this is due to the formation of the weld between the thin outer sheet and the middle sheet. In order to fully understand the behaviour of the electrode displacement during multi-sheet combinations more such experiments needs to be performed. It is important to further investigate how multi-sheet stacks affect the displacement in both symmetric, relatively easy-welded, combinations as well as in more complex cases.

The third interesting part of the curve, the final indentation, has not been in focus in this study. However, it is possible to imagine that the final indentation can be a quality measurement as well, since it can provide information regarding cavities and pores.

In order to implement the electrode displacement as a measurement in the automotive industry, the measuring system is required to be built into the equipment. As shown in this study the equipment from Matuschek with the built-in force sensor provides the same information as the external measuring system, except that the Matuschek system does not have the ability to take the flexibility of the gun arms into account. However, if calibration of the gun arms is performed for the used gun this would not be an issue. In addition to the used Matuschek equipment there are other manufacturers with the same kind of equipment, for example does ARO provide a gun with an in-built force sensor, called ARO 3G-C gun, and ABB is developing a new gun with a force sensor today. There are two common ways to control the electrode force today, one where the electrode position is adjusted by the servo in order to maintain the force during the entire process and one where the electrode position is locked with the prescribed force at the squeeze time. It is important to notice that this method requires an active servo which maintains the electrode force during the entire process by adjusting the electrode position.

9 Conclusions

The results from this study show that the maximum electrode displacement correlates to the quality of the weld. This leads to the possibility to use the maximum electrode displacement as a quality measurement in production, which would increase the safety and decrease the amount of destructive testing. The correlation between the electrode displacement and the nugget size does also imply that the method could be used in the process parameter optimization which possibly could save a lot of time consuming destructive testing. It is also shown that the slope of the curve during the initial phase of the process increases with increased current level. This phenomenon could possibly, with further investigations, be used as an adaptive control system in order to perform an on-line regulation of the current level in order to prevent both spatter and under-developed nuggets.

The results do also show that the used equipment from Matuschek with a built-in measuring system could be used for this kind of measurements. Since this equipment does not require any external measuring equipment it could most likely be implemented in the industry today.

10 Future work

In order to use the electrode displacement as a quality measurement, more tests needs to be performed on several kinds of material combinations. It is highly important to further investigate the phenomenon during welding of multi-sheet combinations in order to fully understand the joint formation in every interface. It is also important to perform tests on all kind of possible combinations in order to evaluate the best way to use this technique as a process parameter optimization tool.

In the case where the method would be used as an adaptive controlling system, several tests needs to be performed in order to fully understand how the initial increase in electrode displacement affects the final quality of the weld. This may also require the development of a system which combines the electrode displacement measurements with the dynamic resistance in order to fully regulate the process parameters adaptively for each weld.

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