The effects of overlap area and surface roughness on metal-composite Friction Spot Weld joints

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Abstract

Previous studies involving friction spot welding of aluminum 7075-T6 and glass fiber reinforced polyphenylene sulfide (PPS) came across a number of inconsistencies in the welding interface after separating them by means of a lap shear tensile test. The interfaces appeared to transition from fully melted and bound to the aluminum to a barely melted and only weakly bound to the aluminum. Furthermore, varying amounts of resin were found to be stuck to the aluminum surface after separation, suggesting a bond strength highly inconsistent over the entire interface. This study aimed to investigate the influence of these appearing transition areas by varying the surface area of the welding interface. The transition area of the PPS was proven to have a negative influence on the bond strength, 10.9MPa average for samples without transition area to 9.34MPa average with transition area. The PPS resin stuck to the aluminum appeared to have a positive influence on the bond strength, but not nearly as much as indicated by previous work. Furthermore, the effect of surface roughness of the aluminum on bond strength was investigated by compressing the aluminum with P60 sanding paper before welding. The resulting bond strengths of 9.13MPa average were very similar to those of the untreated sample, suggesting that a course surface treatment does not improve bond strength.

1. Introduction

Friction stir welding (FSW) and friction spot welding (FSSW) have already been proven a viable method for joining metal objects without raising their temperature to their melting point. Primarily the aviation and automotive industries apply this method for creating lightweight joints between parts. With the ever increasing desire for lightweight materials those industries turn to the use of polymers for non-load bearing applications. However, the physical joining of metals and polymers often create a challenge for the manufacturer. These so-called hybrid joints can be made in traditional ways such as riveting and gluing, but these methods bring along their own problems. Riveting requires damaging the components and can induce stress concentrations, and adhesive joints can deteriorate over time or require the use of hazardous materials. Since FSSW is a solid-state joining technique it can also be applied to these hybrid joints. The metal component never reaches its melting point, where the polymer on the contact interface melts at elevated temperature, flows into the pores of the metal surface and hardens out when cooled, interlocking the two components. This eliminates the use of any hazardous material, does not damage the components and does not alter the mechanical properties of the metal as much as fusion welding.

Friction stir welding involves the use of a rotating tool for generating the friction needed to generate heat. During the process this tool, generally of a high-hardness metal, is pressed down upon the area to be welded and is set to rotate at a set RPM. It is then translated along the weld line, locally heating the metal and creating a weld joint along its path. Increasing the normal force exerted by the tool, the rotation speed, tool size or friction coefficient increases the heat generation rate, and thus the maximum temperature of the process.

Friction spot welding is similar to stir welding, with the exception that there is no translation of the tool, often creating a smaller joint. In this work, FSSW is the method used for the hybrid joining of aluminum 7075-T6 and polyphenylene sulfide (PPS).

This research is intended as a continuation of Liu and Bor's work on the process of friction stir welding. [1] Their work indicated that the use of FSSW is by far the most promising method of three, the other two being Friction Stir Welding and Ultrasonic Welding (US), although literature indicates that strong joints with for example US are also possible.[2]

An interesting result of Liu and Bor's work was the bonding interface of the FSSW Al-PPS samples. After separating the samples in a series of lap shear tensile tests it appeared that the interface was of an inhomogeneous nature, with very different bonding surface areas. Further away from the edge of the aluminum the PPS showed a 'transition area' where the PPS has not fully bonded with the aluminum, see figure 1.1. The inhomogeneous nature of the interface is hypothetically caused by a temperature gradient in the aluminum sample.

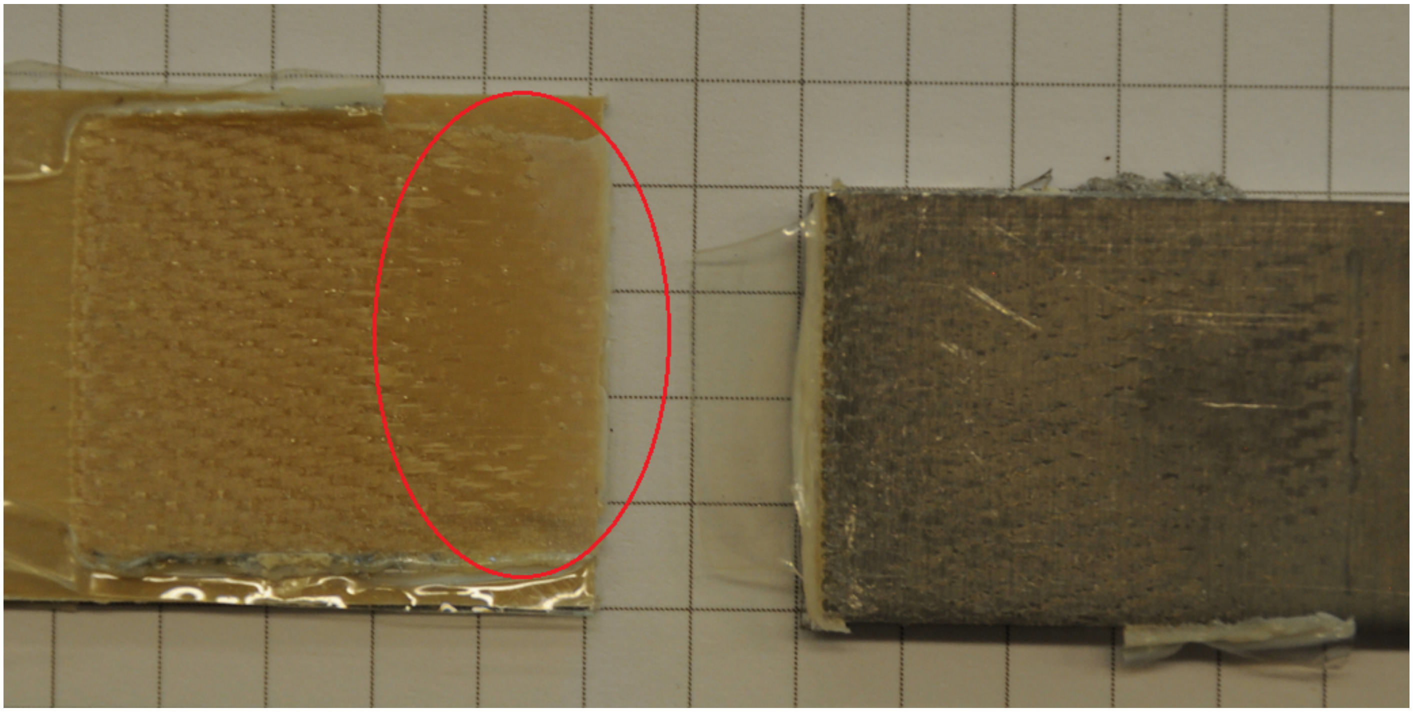

Figure 1.1: The interface area of one of the samples after failure during a lap shear tensile test. The highlighted area shows the transition area where the PPS has not properly bonded with the aluminum.

Liu and Bor's research showed that part of the PPS resin was left on the aluminum samples after breaking the samples on the universal testing machine (UTM). They dubbed this the 'real bonding area', as this area is where the limiting factor of the bond strength is the cohesive forces in the PPS, rather than the adhesive forces between the aluminum and PPS. A roughly linear relation was found between the bond strength and real bonding area, although the influence of the transition area is still unclear.

In further, as of yet unpublished work, Liu compressed aluminum samples with sanding paper with the purpose of leaving a permanent impression of the sanding paper on the aluminum surface, thus increasing the surface roughness. Theoretically this should increase the bond strength between the PPS and the aluminum due to an increase in bonding area, but the parameters of the compression process are not known, making it difficult to assess the influence of surface roughness on bond strength. In the past, other studies used a careful abrasion with fine sanding paper, usually around P1200, to remove the aluminum oxide layer and increase surface roughness [3][4] but this study will be aimed at more course sanding paper.

To summarize, the following questions are addressed in this work:

- How does the size of the transition area influence the bond strength between Al7075-T6 and GF PPS?
- How does a surface treatment, creating a coarse surface influence bond strength.

To study the influence of the transition area several series of friction spot welds were made, each series with the same interface geometry (a rectangular patch) but different overlap areas. This should reduce the presence of the temperature gradient over the welding area, creating a more homogeneous interface and likely increasing the bond strength. The welded samples are then subjected to a lap shear tensile test in a universal testing machine (UTM) to investigate the bond strength.

Furthermore, a series of blank aluminum samples were given a surface treatment by pressing a small patch of sanding paper down upon them. This left a permanent impression of the sanding paper on the aluminum surface, increasing the surface area and possibly the bond strength with the PPS. These samples are then welded and tested in the UTM as usual.

This report covers the experimental setup and its relevant parameters and the results from the measurements during welding and after the lap shear tensile tests. The PPS samples are checked for any transition areas, and the aluminum samples are checked for real bonding area. These results are then presented presented such that a conclusion may be drawn. Lastly, a series of recommendations and improvements for future work in this field are made.

2. Experimental setup and materials

2.1 Welding process

Since the welding process does not involve any translation along a weld line and only a series of spot welds, the friction spot welding method is selected for this research. The welding tool will be applied to the aluminum sample, which is mechanically far more resilient to the frictional forces generated than the PPS sample. The tool itself will be the only means of clamping the aluminum and PPS together during the process i.e. the samples will not be clamped together.

As mentioned, several series of samples will be welded, each series having its own specific overlap distance.

2.2 Sample preparation

All the aluminum 7075-T6 samples for the single spot weld tests were stamped from a single blank plate into dimensions of 100×20×4mm (L×W×T), whereas the samples for the continuous weld were stamped to dimensions of 200×20×4mm

The Al samples for the generic overlap tests did not receive any surface treatment. The samples for the sanding paper tests were compressed with a piece of P60 sanding paper over an area of 40×20mm by means of a universal testing machine (UTM). The maximum force of the UTM equaled 100kN, resulting in a pressure of 125MPa. Although this pressure was well below the 500MPa tensile strength of Al7075-T6, it was enough to leave a permanent impression onto the Al samples.[5] After compressing the samples, any residual grains that separated from the sanding paper were wiped from the Al surface.

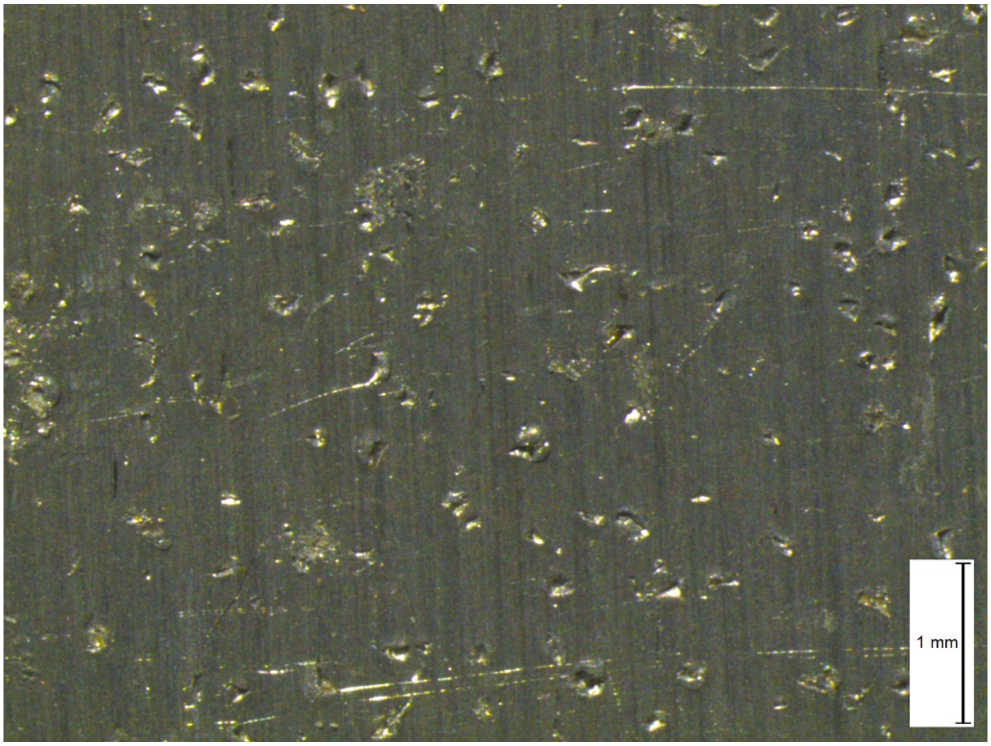

Figure 2.1: A close-up of the surface of an Al sample after compression with grit 60 sanding paper.

As evident from figure 2.1 the crevices are clearly of low frequency, approximately 5 to 6 indentations per mm^2, but their amplitude can be considered high due to the coarse nature of the sanding paper. Due to a lack of time it was not possible to determine the depth precisely, however, and the surface roughness is not quantitatively stated.

All the Al samples had a hole drilled in the side to accommodate a K-type thermocouple to constantly measure the temperature during the welding process. This hole was approximately 1mm wide and 10mm deep, and situated 12±1mm from the edge of the Al sample. This small deviation was due to the hole being drilled by hand on a rough surface, inducing some inaccuracy. For the smaller overlap experiments the hole was drilled at 10mm and 8mm from the edge. The thermocouples were glued into place using heat resistant glue.

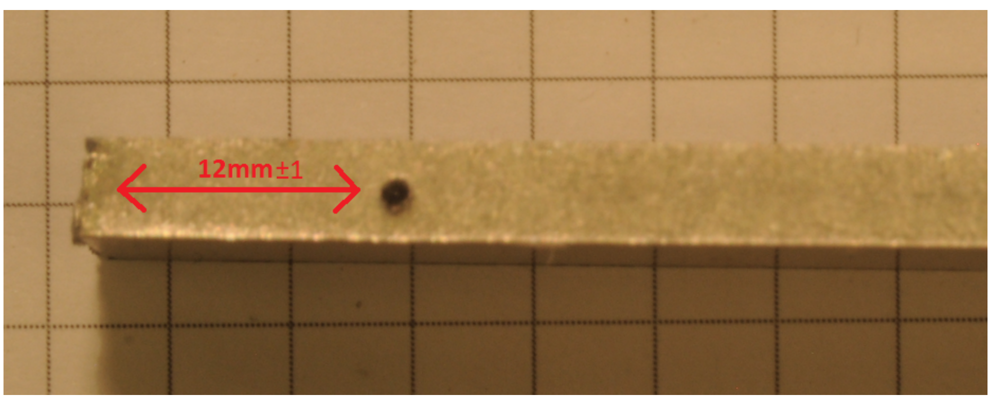

Figure 2.2: The hole to house the thermocouple.

The glass fiber reinforced PPS samples for the single spot weld tests were cut from a single plate into dimensions of 120×25×2mm. The continuous weld samples were cut into dimensions of200 ×20×4mm (similar to the Al samples). All PPS samples were cut in the same lengthwise orientation of the plate and received no surface treatment.

In addition a thin foil (40μm) of pure PPS is placed between the Al and PPS before welding. This is done to ensure sufficient amounts of resin to flow and bond with the Al surface.

All the samples were cleaned with acetone before setting them up for welding.

2.3 FSSW setup

The PPS sample was first put in place under the welding tool, after which the area to be welded was covered with a piece of pure PPS foil. The Al sample was placed on top of the PPS such that the overlapping distance equaled either 15, 20 or 25mm (depending on the series of the experiment). This setup can be schematically seen in figure 2.3. The aluminum and PPS samples were separately clamped down to prevent them from shifting during the actual welding.

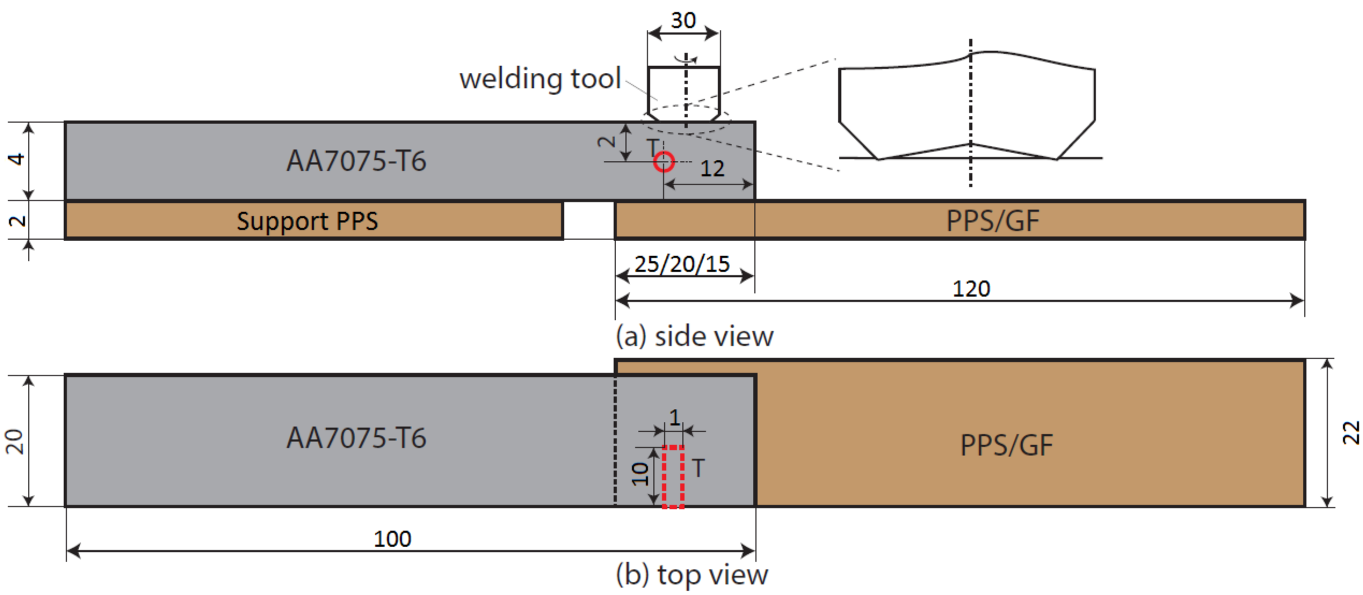

Figure 2.3: Schematic representation of the FSSW setup during welding. The red circle indicates the hole drilled for the thermocouple. Tool size not drawn to scale, all measurements are in mm. Figure adapted and edited from Liu and Bor.[1]

The smaller piece of PPS labeled 'Support PPS' serves to level the Al sample during the experiments.

After the samples were sufficiently clamped down the K-type thermocouple (indicated by a red circle in figure 2.3a) was connected to a National Instruments Data Collection System to measure the temperature at a frequency of 10Hz. The Data Collection System output was fed into Labview for later analysis.

Next the welding tool was pressed down onto the Al surface at a 0° angle, such that its center was positioned 15mm from the Al edge. The force with which the tool was pressed down varied from series to series, but was of the order of 1-2.5kN. Once the desired downward force was reached the tool was set to rotate at 700RPM.

The desired maximum temperature was approximately 360°C Based on the immediate feedback from the thermocouple the tool was shut down at 325°C, where the tool's inertia and the fact that the thermocouple was not in direct contact with the surface caused the temperature to rise to 360°C. Occasionally this was not the case, which will be indicated in the graphs.

Additionally, the P60 surface treated Al samples were chosen to have a specific overlap distance of 20mm to compare them to the results of the bare 20mm overlap tests. Any other parameters were kept unchanged.

2.4 Lap shear tensile test

The bond strength of the single spot weld samples were tested by means of a UTM. The samples were clamped according to figure 2.4. The clamps are misaligned on purpose to ensure the interface area is directly in line with the red centerline in the figure. Once clamped, the machine was set to move at 0.5mm per minute until failure occurred.

This testing method is far from ideal, since the upward and downward forces do not engage directly on the interface plane, but are misaligned and subsequently create a moment that peels the Al and PPS from each other. The test is therefore less accurate than desired, and its results should only be used as an indication rather than solid proof.

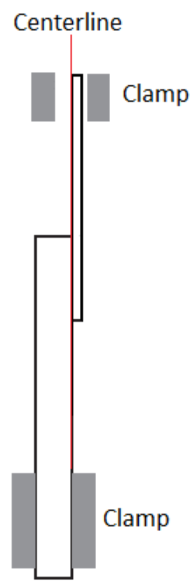

Figure 2.4: Schematic representation of the clamping mechanism used to test the weld samples on the UTM. Figure adapted and edited from Liu and Bor.[1]

3. Results and discussion

A total of 22 tests have been performed, with all samples numbered according to the order in which they were welded. See table 3.2.

Table 3.1: The sample numbers and their relevant testing parameters

Series	Sample numbers	Overlap distance (mm)	Interface area (mm^2)	Surface treatment
1	01-06	25	500	X
2	08-10, 12-14	20	400	X
3	17-22	15	300	X
4	23, 24, 26, 27	20	400	P60 compression

Table 3.2: The sample numbers and their relevant testing parameters

Note that according to table 3.2 the samples 07, 11, 15, 16 and 25 do not exist. Those samples were either destroyed during the experiments or had defective thermocouples and do not appear in the results. Futhermore, all the spot welds were made with the tool set at 700RPM, except series 1 of the samples. The RPM value was not recorded and is unknown, but judging from the temperature over time results discussed later it was of the same order of magnitude.

3.1 Welding measurements

The resulting temperature and force over time are represented in figure A.1 to A.8 in appendix A. An example is elaborated upon below. Most samples show this consistent pattern in their force graphs. Before welding actually starts the force has to be set manually to the desired value. The only way of doing so is by moving the machine down towards the samples, and it requires some trial and error. In figure 3.1, the first 120 seconds are used to set the normal force of the tool, and are irrelevant to the welding process itself. The moment the welding process starts (140 seconds in) and the tool starts rotating the normal force drops due to the tool scraping away at the aluminum surface. This creates a circular recess in the sample, reducing the normal force. Then the tool actually starts heating the aluminum, the thermal expansion causing the normal force to increase. Once the PPS melts the normal force levels due to the resin flowing away from the pressure points. After the tool stops rotating the normal force slowly drops until it has reached the approximate melting point of the PPS, where it drops of dramatically. This sudden drop is credited to the PPS solidifying and finally shrinking, and is a good indication of the point in time where the PPS transitions from liquid to solid. Note that this is not entirely accurate since the temperature graph is that of the aluminum, and not of the Al-PPS interface. The difference in temperature between the two will be very small and therefore neglected in the analysis. Afterwards the samples cool steadily, with the cooling rate decreasing over time without any other indication of a phase transition, as expected.

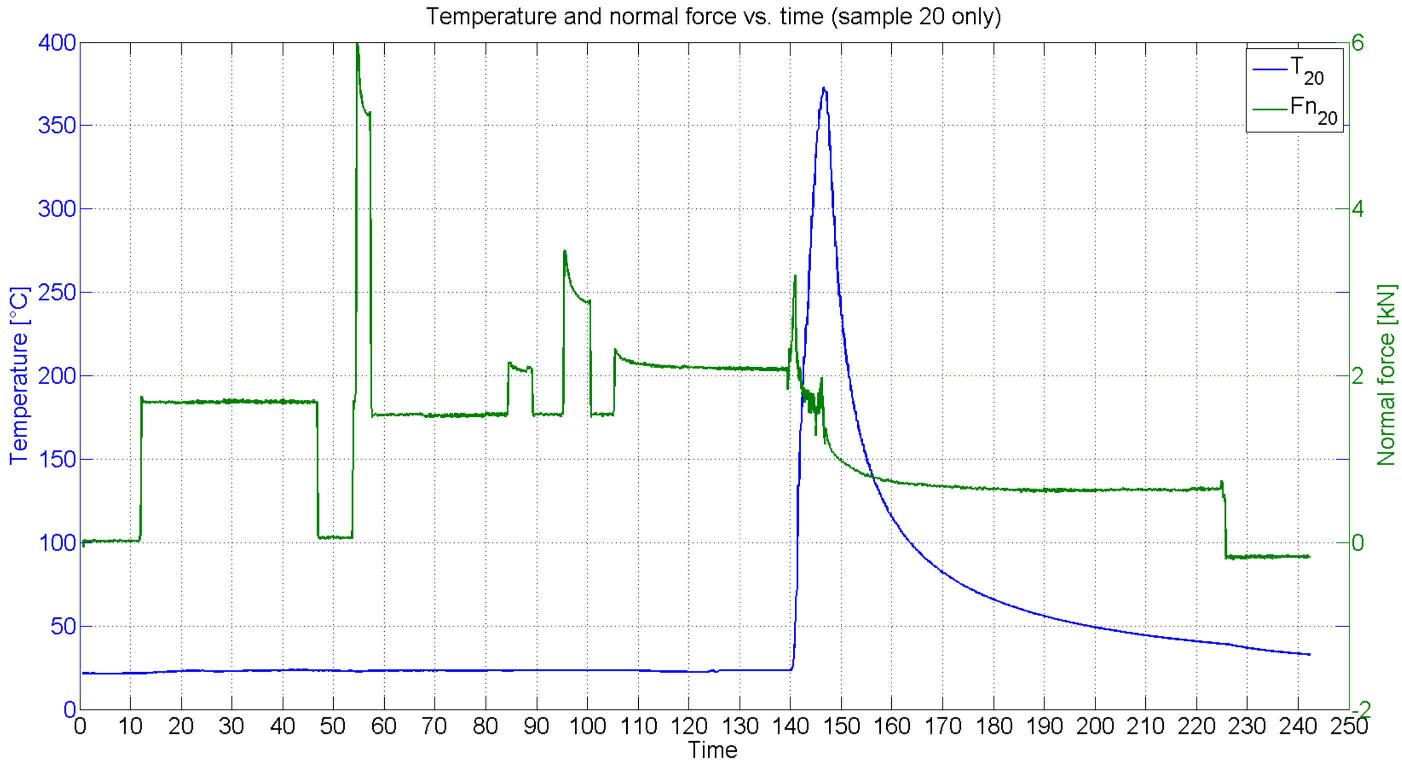

Figure 3.1: An example graph of sample 20's temperature and normal force over time.

From figure A.5 it appears that sample 22's thermocouple was damaged or detached during welding.

3.2 Lap shear tensile test results

All lap shear tensile tests were performed with a clamp travel speed of 0.5mm/min. Observation of the lap shear tensile tests on the UTM revealed that all samples rapidly dismembered once reaching their maximum force (less than a second), often accompanied by an audible noise. Some of the PPS and Al samples were still stuck together by the pure PPS foil's edges, but this did not contribute to the bond strength and was easily separated by hand. The results from the UTM are listend in table 3.3.

Sample	F_{max} (N)	Bond strength (MPa)	Sample	F_{max} (N)	Bond strength (MPa)
1	16	0.032	14	3064	7.66
2	4422	8.84	17	3898	12.99
3	4456	8.91	18	1228	4.09
4	4726	9.45	19	1320	4.40
5	5024	10.05	20	3086	10.29
6	4811	09.57	21	3379	11.26
8	3168	7.92	22	2850	9.50
9	4312	10.78	23	4418	7.72
10	4207	10.52	24	4358	10.89
12	4085	10.22	26	3186	7.96
13	3566	8.92	27	2950	7.37

Table 3.3: UTM results from the lap shear tensile tests

Typical maximum failure loads for the 25mm overlap samples are from 4.5kN to 5kN. The maximum failure load of series 2 and 3 are smaller, 3kN to 4kN and 1.2kN to 3.9kN, respectively. This is as expected, since these samples have a smaller bonding area.

Samples 24 and 27 were misaligned during welding, resulting in the Al and PPS samples being rotated with respect to each other with an angle of approximately 10°. This rotated orientation will result in an additional moment being applied by the UTM during the tensile tests, resulting in an inaccuracy in the maximum failure load. Therefore sample 24 and 27 alone cannot be used to draw conclusions from, but they will not be neglected considering the small size of series4.

Sample series 1 (samples 01 to 06) show reasonably consistent bond strengths (excluding sample 01), with an average of 9.4MPa.

Series 2 (samples 08 to 14) with a 20mm overlap area show bond strengths consistent with series 1, although there appears to be a higher deviation from the average of 9.3MPa.

Sample series 3 (samples 17 to 22) with a 15mm overlap area shows promising results with bond strengths reaching nearly 13MPa. Clearly, samples 18 and 19 are very inconsistent with this trend. Looking back at the welding graphs of series 3 (figures A.5 and A.6) their temperatures were slightly below the other samples of this series, but their normal forces during welding were significantly less than the other ones (only slightly over 1kN opposed to over 1.5kN). More importantly, the force exerted on samples 18 and 19 dropped very low during the cooling process (hardly 200N). This weak force might have prevented the molten PPS from sticking to the aluminum and could have led to the low bond strength.

Note that samples 20, 21 and 22 had significantly higher normal forces the moment welding started. This was due to the tool not being able to reach the desired temperature under standard conditions. It is unknown why this was the case, but increasing the normal force had the desired effect of the tool reaching adequate temperatures again. This higher normal force could lead to a higher bond strength and inconsistent results, but this is unlikely since their normal forces at the 280°C mark during cooling (the melting point of PPS [6]) is similar to the other samples. Even though the normal force of samples 20 to 22 did not drop to terminal values as low as the other samples in series 3, the effect on the bond strength is considered small since this inconsistency occurs when the PPS has already solidified.

Discarding samples 18 and 19 gives an average bond strength of 11.5MPa Sample 22 is not taken into account for this analysis since its temperature and force graph are erroneous.

3.3 Interface appearance

After the lap shear tensile tests the bonding interface areas were visible for inspection, revealing the degree of resin flow and the area of the aluminum covered by resin. The interfaces can be seen in figures B.1 to B.4in appendix B. Although the resin coverage of the aluminum samples are not entirely clear from the photographs, it was measured and calculated by hand from the real samples.

Figure 3.2 shows the decrease in transition area for decreasing overlap area. Mainly sample 20 with the 15mm overlap shows no transition area whatsoever. The samples are taken from series 1, 2 and 3, respectively.

Most of the samples show a dramatic change in PPS surface structure after welding. For example, PPS sample 09 shows that the entire welding surface has melted as the glass fiber structure is visible throughout the entire welding surface. However, its aluminum counterpart has only an approximate 170mm^2, 45% real bonding area. Sample 06 in series 1 shows a similar surface of its PPS with only a small transition area near the edge, but a much higher real bonding area on the aluminum (around 380mm^2, 72%). Yet the bond strengths were very similar (9.57MPa vs. 10.78MPa for 06 and 09, respectively). Sample 09 reached a higher temperature during welding (395°C vs. 375°C), but a lower (and more stable) normal force. This trend appears throughout sample series 1 vs. 2, with series 1 having a significantly higher real bonding area, but bond strengths very similar to series 2.

Sample series 3 show significant decrease in transition area but little increase in real bonding area, percentage wise. The increase in bond strength suggests the importance of the transition area, negatively affecting the bond strength.

Series 4 is statistically a very small batch to actually draw conclusions from, but it is nevertheless interesting to note that there was no increase in resin stuck to the aluminum surface. Despite the fact that sample 23 showed significant damage to the PPS sample after the lap shear tensile test. This would suggest a very strong bond between the PPS and aluminum, but the bond strength from table 3.3 is similar to that of sample 24, and close to the average of series 2. This is a very surprising result, especially considering that the glass fibers in the PPS were torn perpendicular to their orientation. So far, the only explanation is that the PPS sample itself was of poor quality.

3.4 Real bonding area vs lap shear stress

Now that the real bonding area is known from inspection of the interfaces it is possible to plot the failure load vs. real bonding area. Liu and Bor found a linear relationship between lap shear failure load and real bonding area. In figure 3.3 this is also present, albeit far less steep than theirs. This is excluding the 3 anomalies of series 3 (green dots).

The reduced overlap area in series 2 and 3 seems to increase the bond strength. Especially series 3 showed very little transition area on its PPS samples, and despite having only 15mm overlap it still has failure loads similar to those of series 2 with 20mm overlap. The transition area is most likely caused by the temperature gradient in the aluminum, and both appear to have a negative effect on the bond strength.

Lastly, it appears that the surface treatment of the sanding paper compression of series 4 does not alter the bond strength, since those results are very similar to those of series 2 (both 20mm overlap).

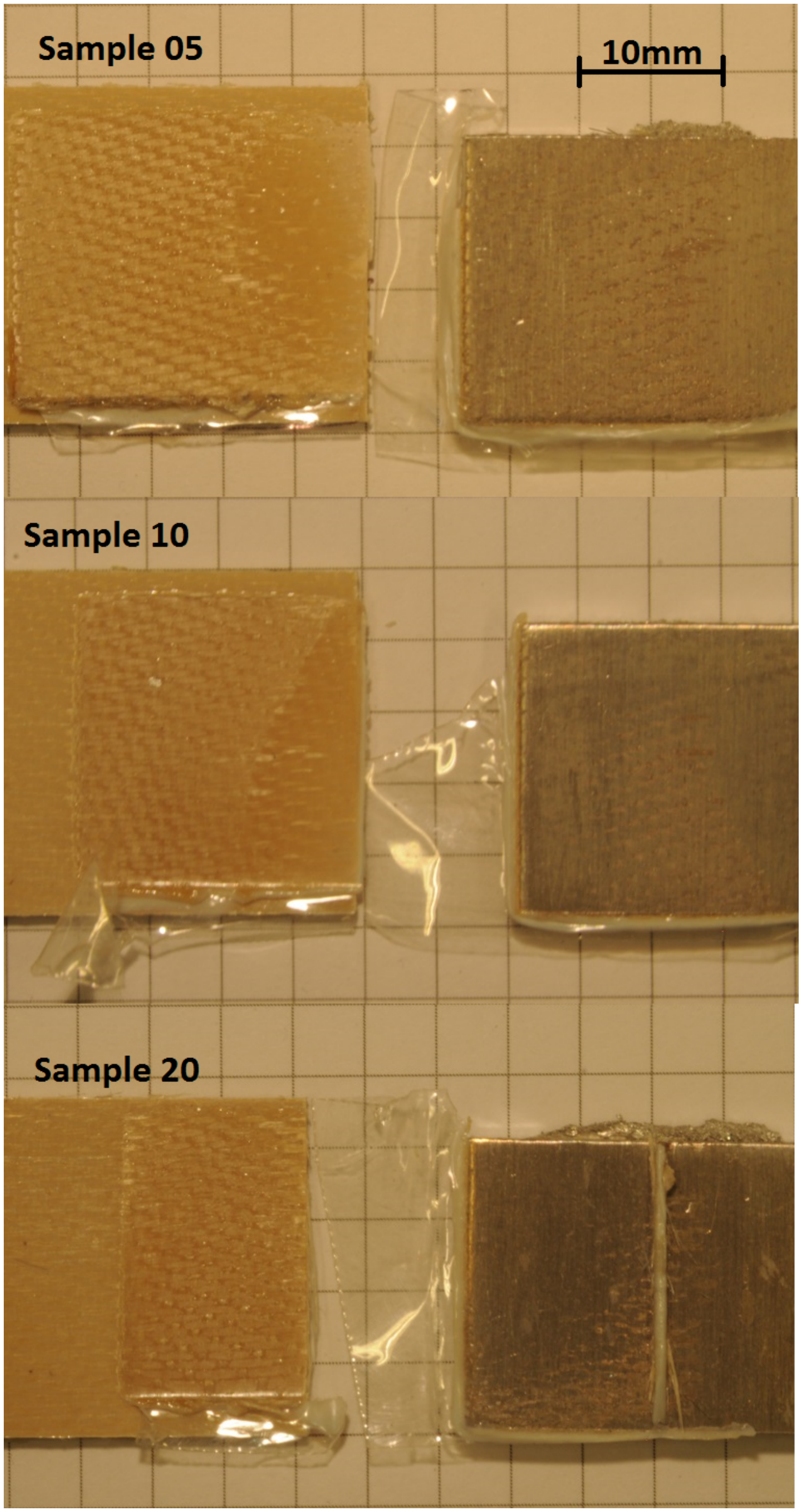

Figure 3.2: Interface appearance of samples 05, 10 and 20 (series 1, 2 and 3, respectively). Note the decrease in transition area for smaller overlap area

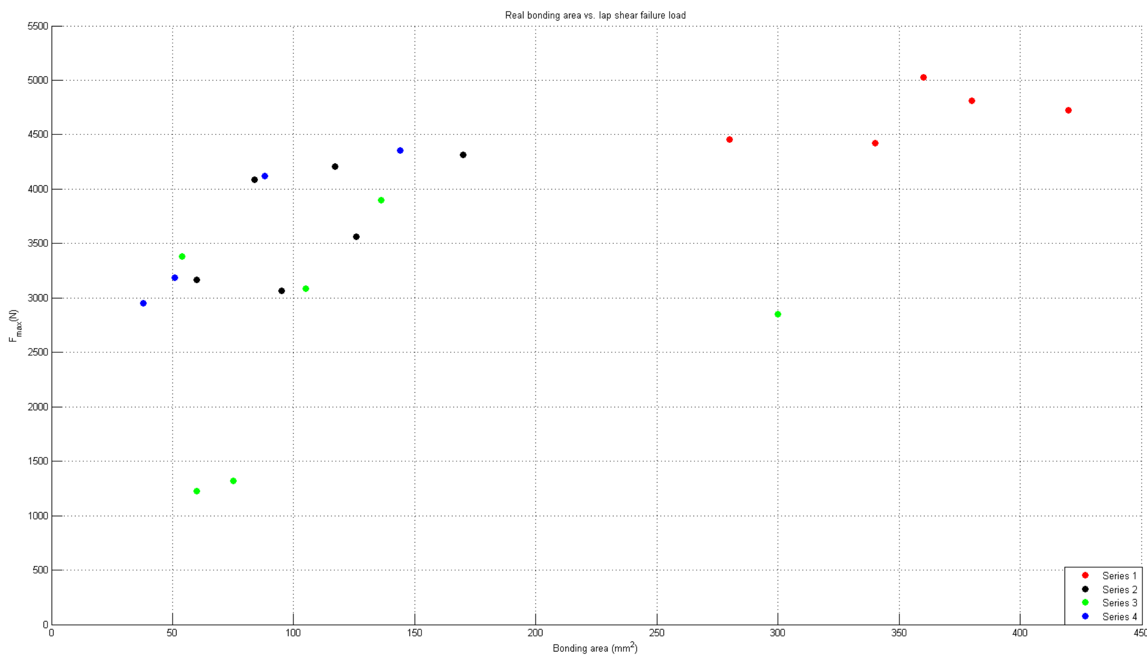

Figure 3.3: The lap shear failure load vs. the real bonding area of all samples.

4. Conclusion and recommendations

4.1 Conclusion

The amount of reliable data from the experiments is not ideal, especially with series 3 giving only 3 samples in line with the other series, and series 4 only 2 reliable samples. Nevertheless, a number of conclusions can be made and several trends can be seen from the data.

- A smaller transition area (figure 1.1) leads to a higher bond strength.
- The real bonding area increases the bond strength, but not as much as expected according to Liu and Bor.
- A high amplitude low frequency surface abrasion appears to neither increase nor decrease bond strength.
- A higher normal force during cooling appears to increase bond strength.

4.2 Recommendations

Although certain relations between bond strength and bonding area became clear throughout the sample series, the batch sizes were relatively small. Especially the sample series that received a surface treatment was too small to actually draw solid conclusions from. It is wise for future research to increase the batch sizes, considering how fragile the samples were.

The sanding paper surface treatment did not give the expected result of an increased bond strength. As stated before, the surface treatment resulted in high amplitude low frequency abrasions, which possibly did little to actually increase the surface area available for bonding. A higher grit sanding paper such as P1200 used by Goushegir et al. treatment might positively affect the bond strength by increasing the surface area.

In addition to using the sanding paper compression treatment, grit blasting might improve the bond strength in the same way. This is a more promising method than the sanding paper compression due to the creation of a highly irregular surface with many peaks instead of purely indentations.

Electrochemical treatments such as phosphoric acid anodizing massively increase the surface area of an aluminum surface by creating a thick layer of porous aluminum oxide. This increased surface area may increase bond strength, provided that the normal force applied is large enough. The surface indentations are on a microscopic level, and the PPS' viscosity might limit its ability to flow into the pores at normal pressure.

Lastly, a factor of inconsistency was the normal force exerted by the tool on the samples during welding. The force graphs show great fluctuations in force for several samples, and it was difficult to precisely set the tool height to reach the desired normal force during welding. A feedback controlled actuator in the welding setup could fix this problem, keeping the force constant not only from sample to sample, but also throughout a single weld.

Now that it is known that a 15mm overlap gives more favorable results than either a 20mm or 25mm overlap it is possible to create a continuous weld using multiple overlapping spot welds. Liu and Bor have proven that creating a continuous weld by means of friction stir welding gives very low bond strengths, primarily due to the thermal stresses induced by the thermal expansion along the welding track. Using multiple spot welds should reduce these stresses and deformations by allowing the samples to cool down inbetween the welds. These continuous welds' bond strengths can be investigated by a double cantilever beam test.

Bibliography

[1] S. Liu and T.C. Bor. Friction stir and ultrasonic welding of composite materials, 2013.

[2] S. Kruger, G Wagner, and D. Eifler. Ultrasonic welding of metal/composite joints. *Advanced Engineering Materials*, 6(3):157–159, March 2004.

[3] B.C. Rincon Troconis and G.S. Frankel. Effect of roughness and surface topography on adhesion of pvb to aa2024-t3 using the blister test. *Elsevier*.

[4] S.M. Goushegir, J.F. dos Santos, and S.T. Amancio-Filho. Friction spot joining of aluminum aa2024/carbon-fiber reinforced poly(phenylene sulfide) composite single lap joints: Microstructure and mechanical performance. *Elsevier*.

[5] Rafael Nunes and J.H. Adams. Properties and selection: Nonferrous alloys and special-purpose materials, 1992.

[6] Koninklijke TenCate. Cetex tc1100 pps resin system datasheet, 2014.

Appendices

A. Welding measurements

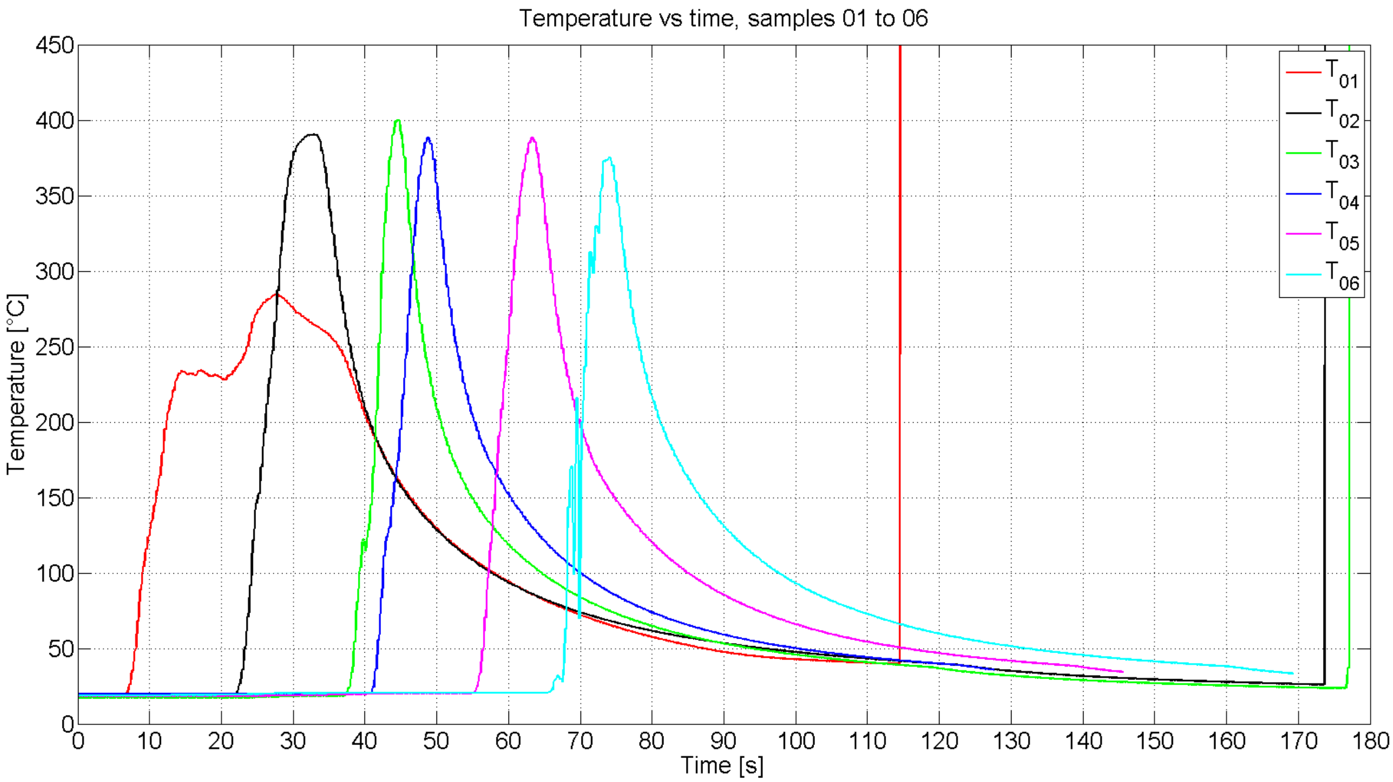

Figure A.1: Temperature over time in samples 01-06 during welding.

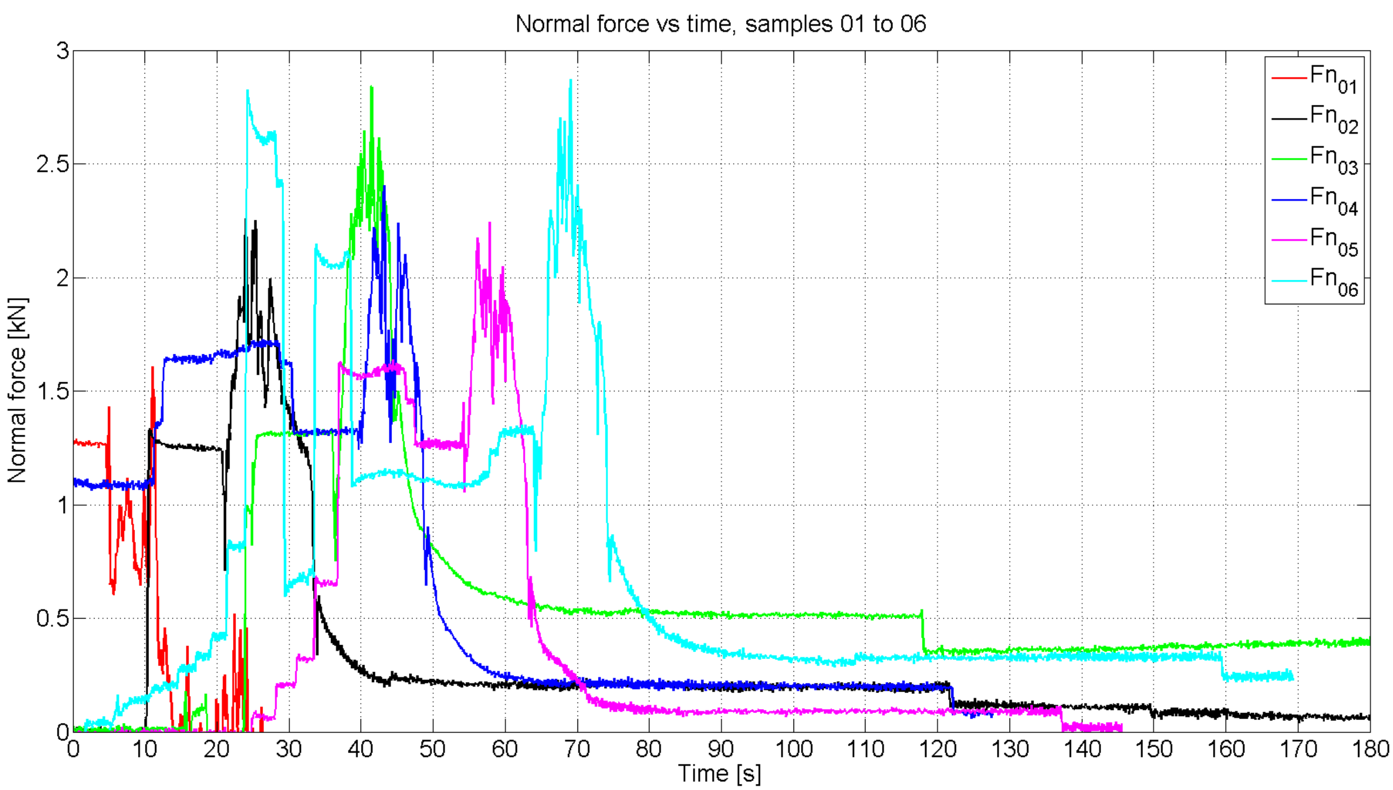

Figure A.2: Normal force over time in samples 01-06 during welding.

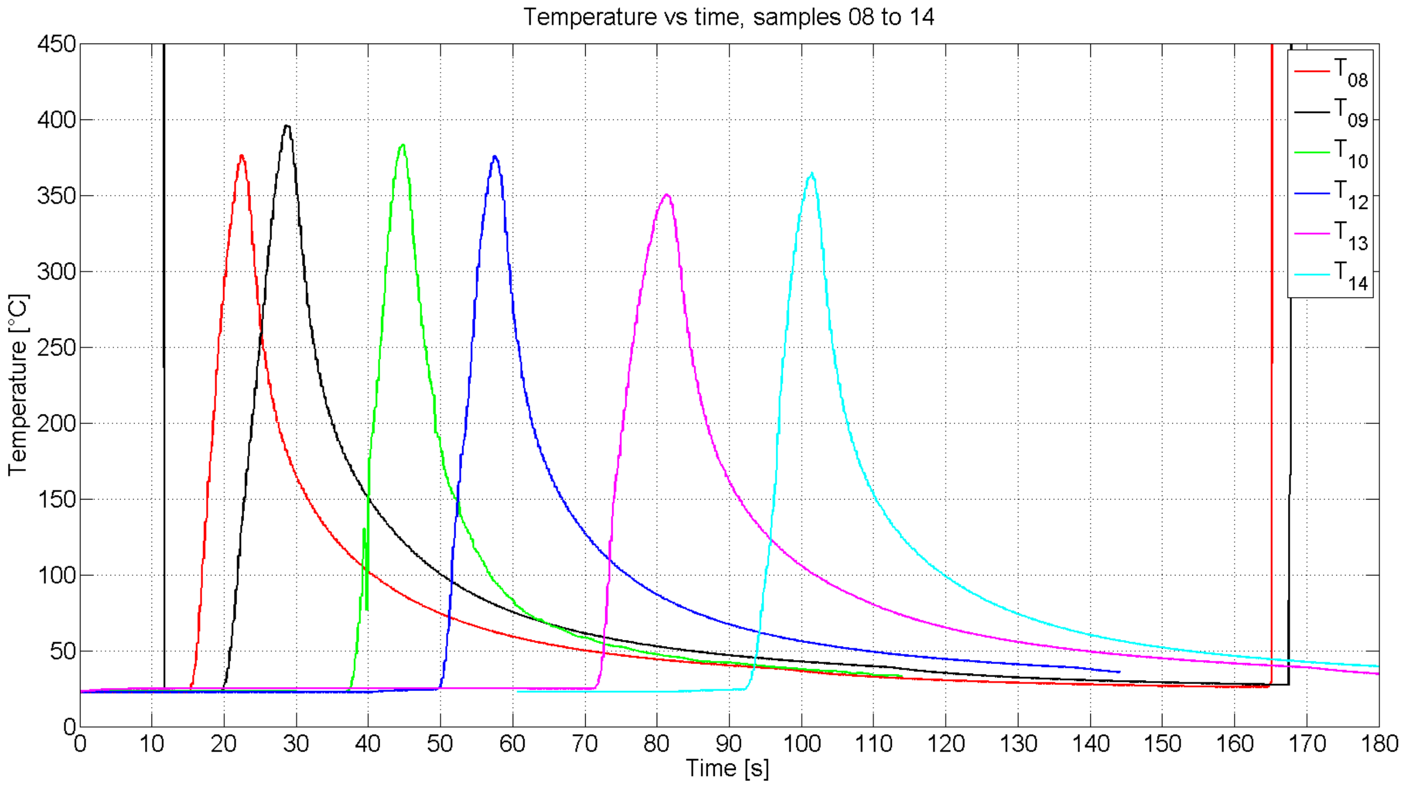

Figure A.3: Temperature over time in samples 08-14 during welding.

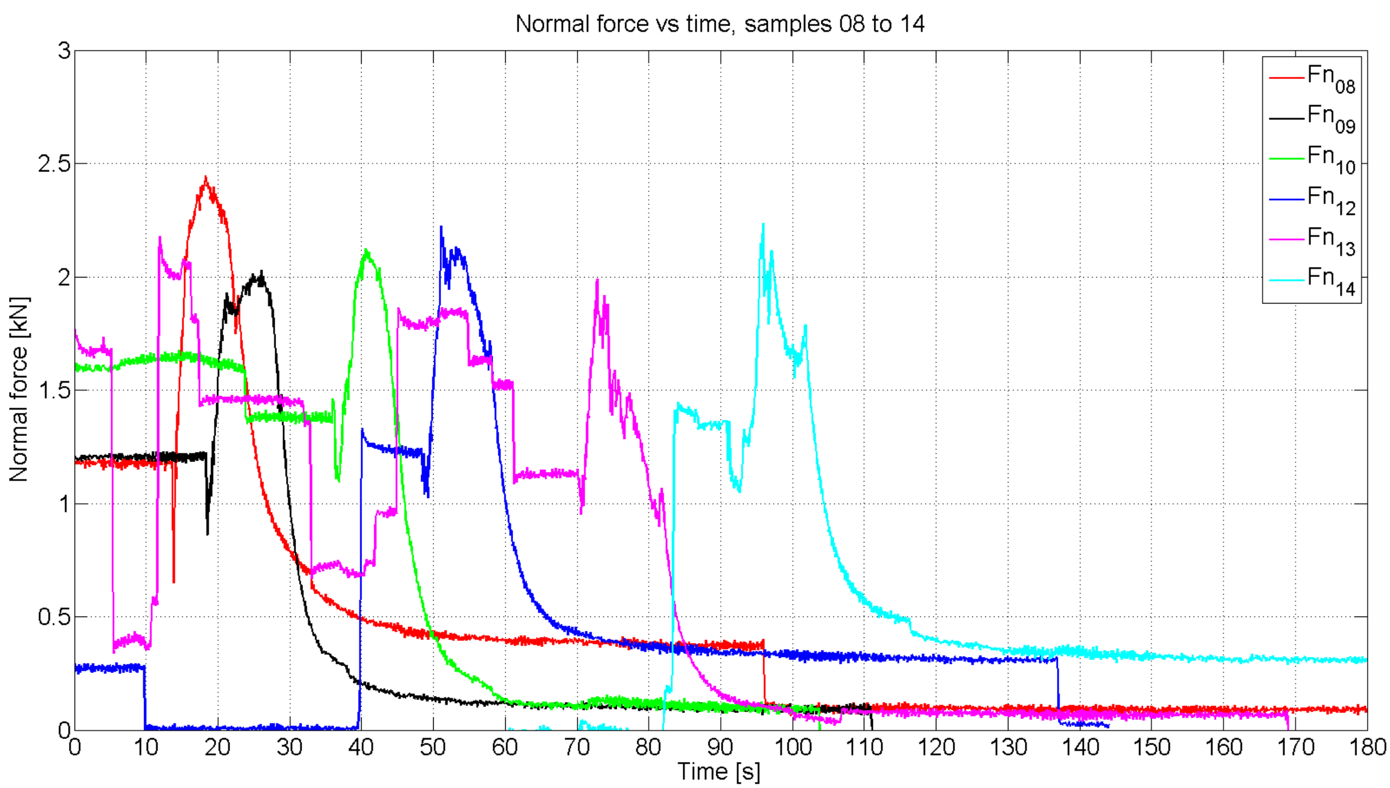

Figure A.4: Normal force over time in samples 08-14 during welding.

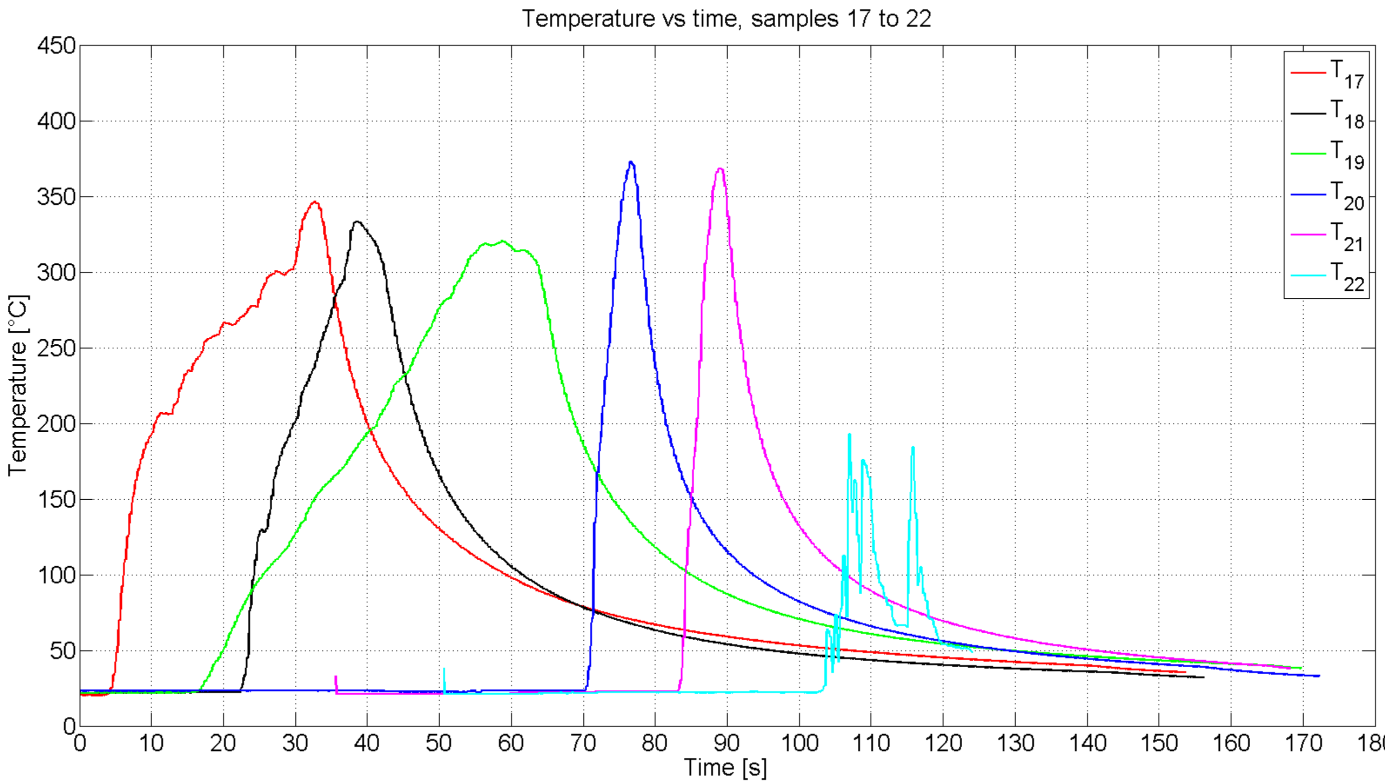

Figure A.5: Temperature over time in samples 17-22 during welding.

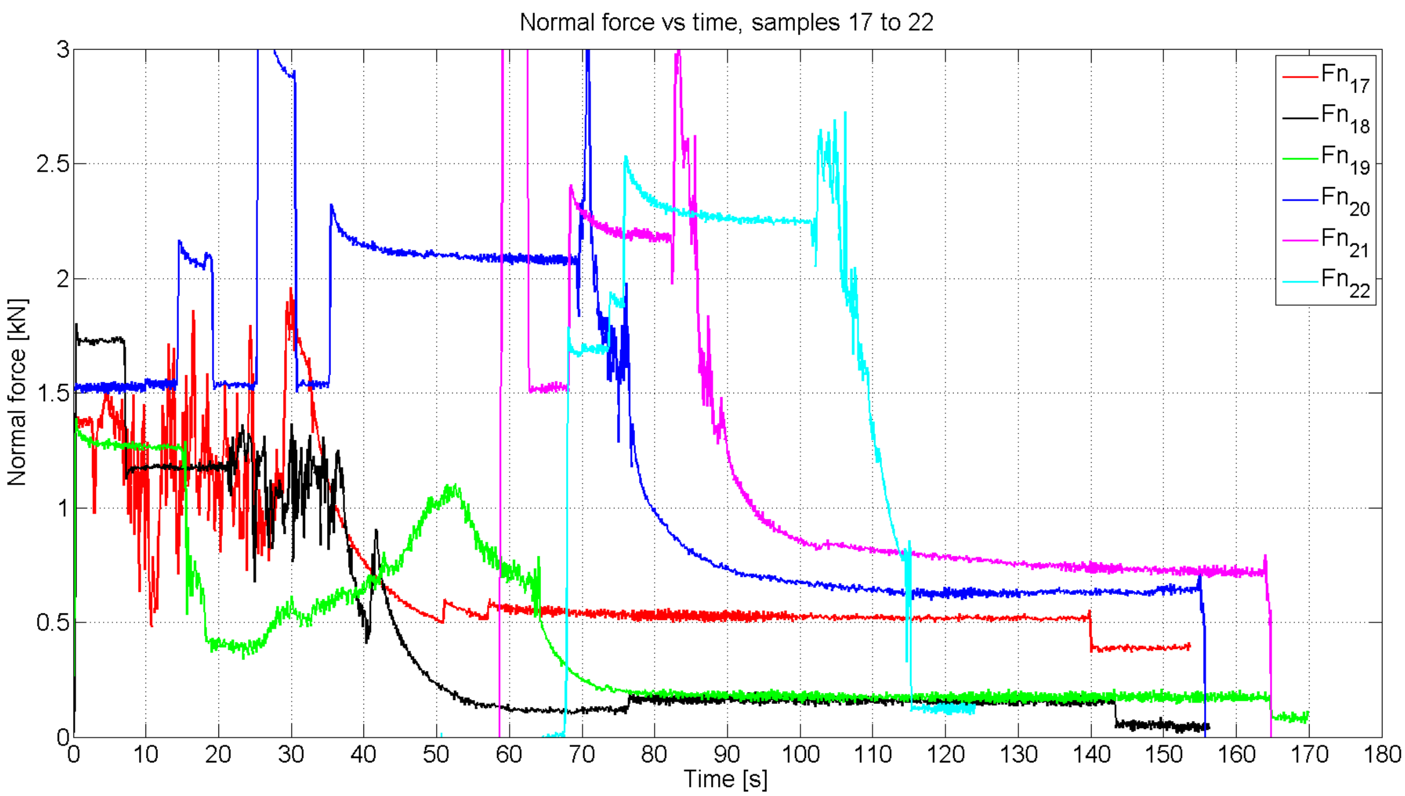

Figure A.6: Normal force over time in samples 17-22 during welding.

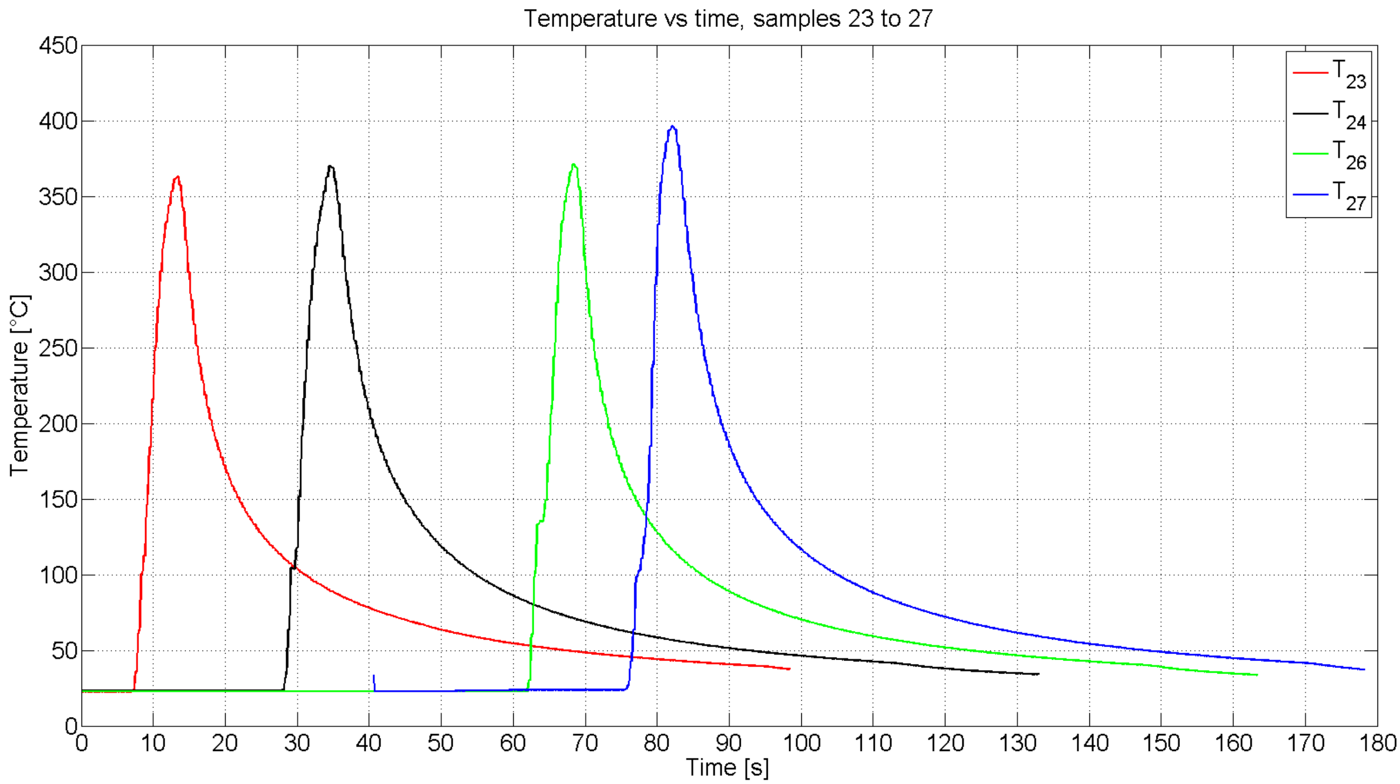

Figure A.7: Temperature over time in samples 23-27 during welding.

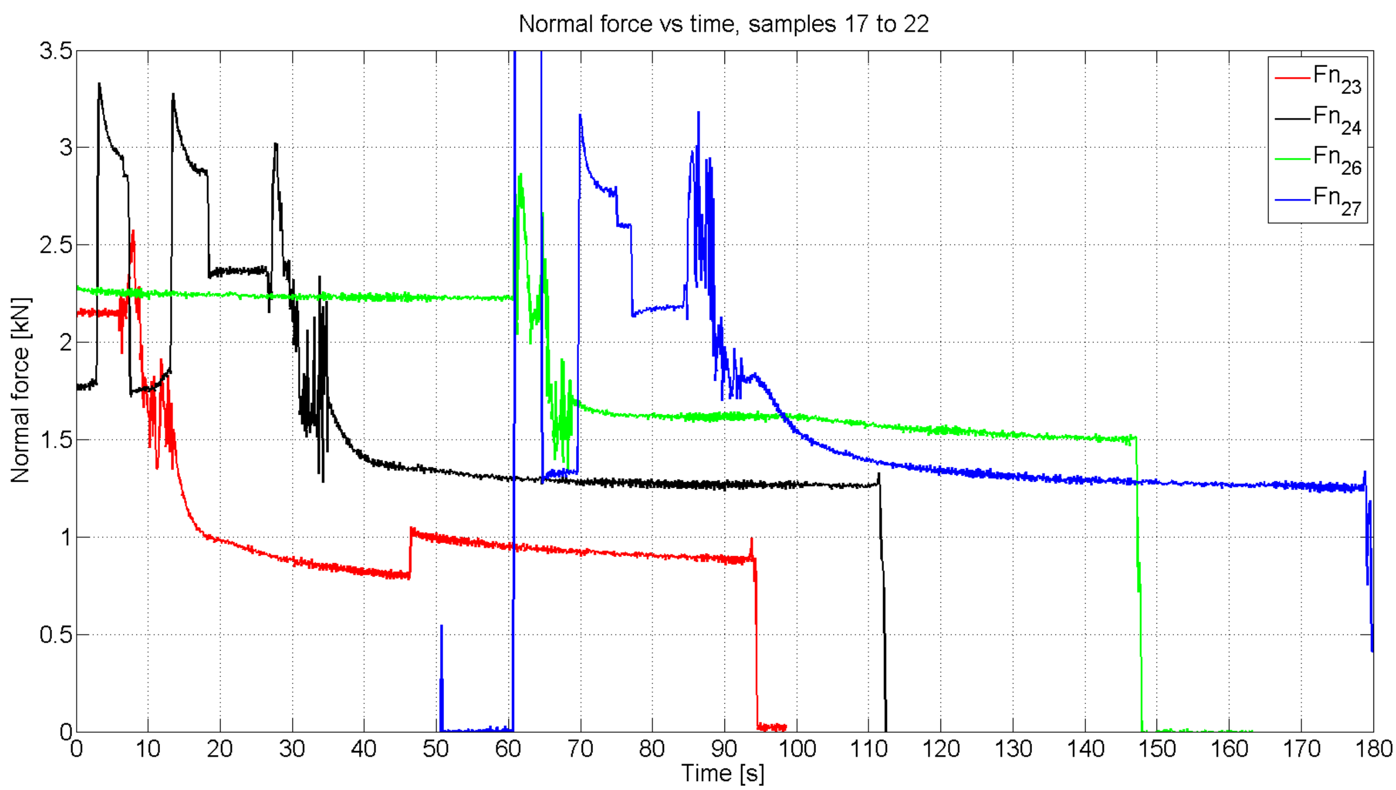

Figure A.8: Normal force over time in samples 23-27 during welding.

B. Interface appearance

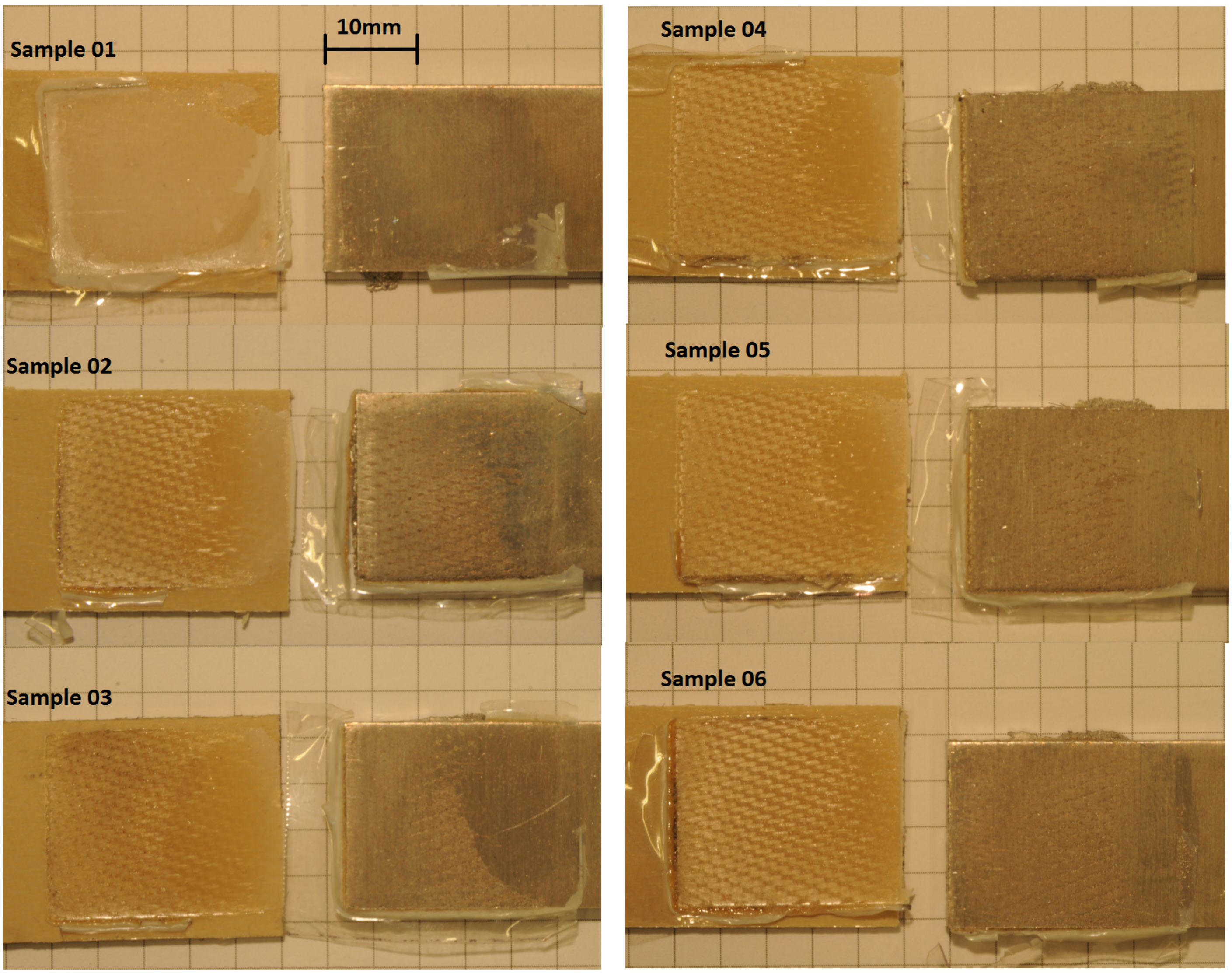

Figure B.1: Interface appearance of samples 01-06, series 1.

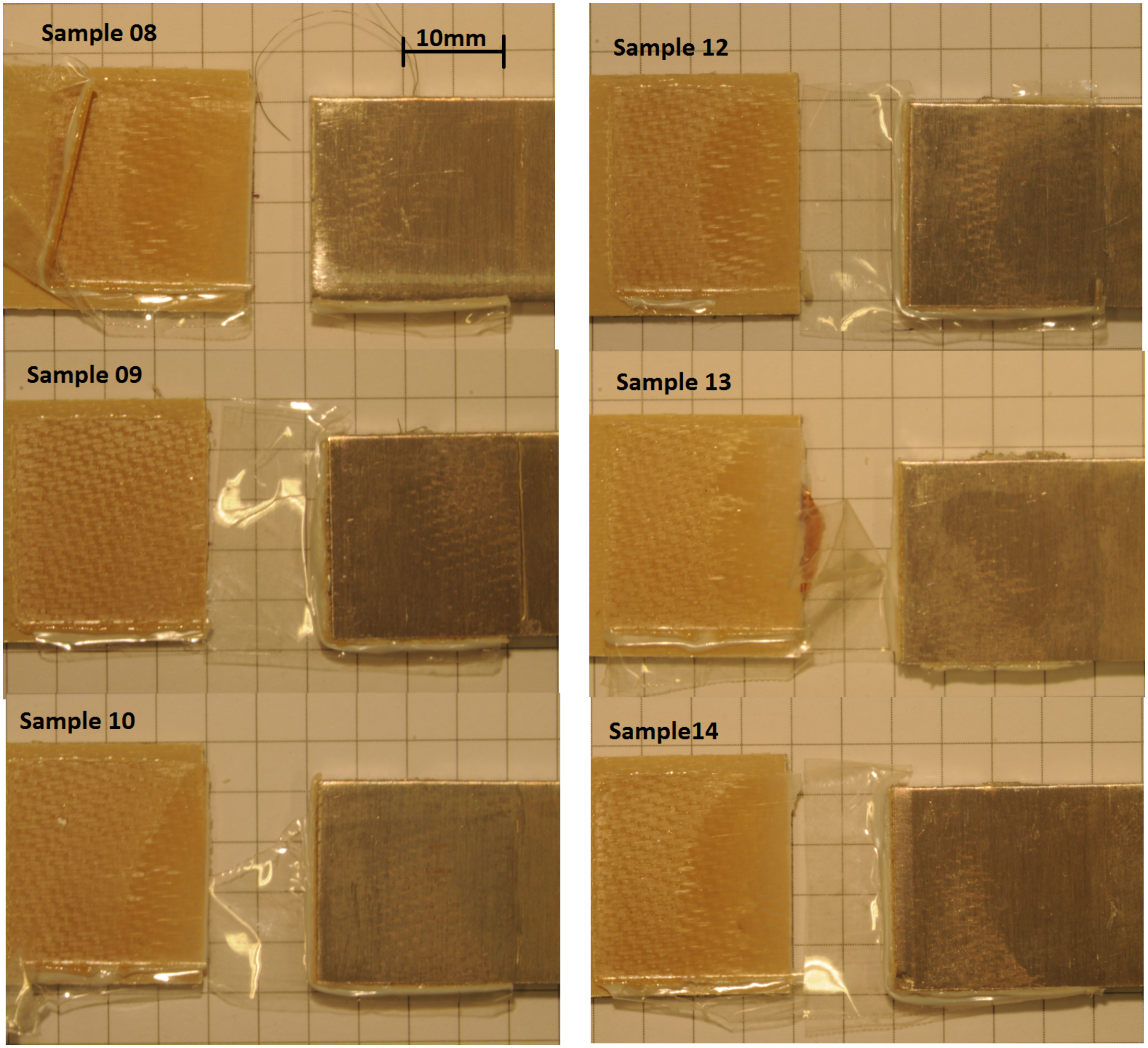

Figure B.2: Interface appearance of samples 08-14, series 2.

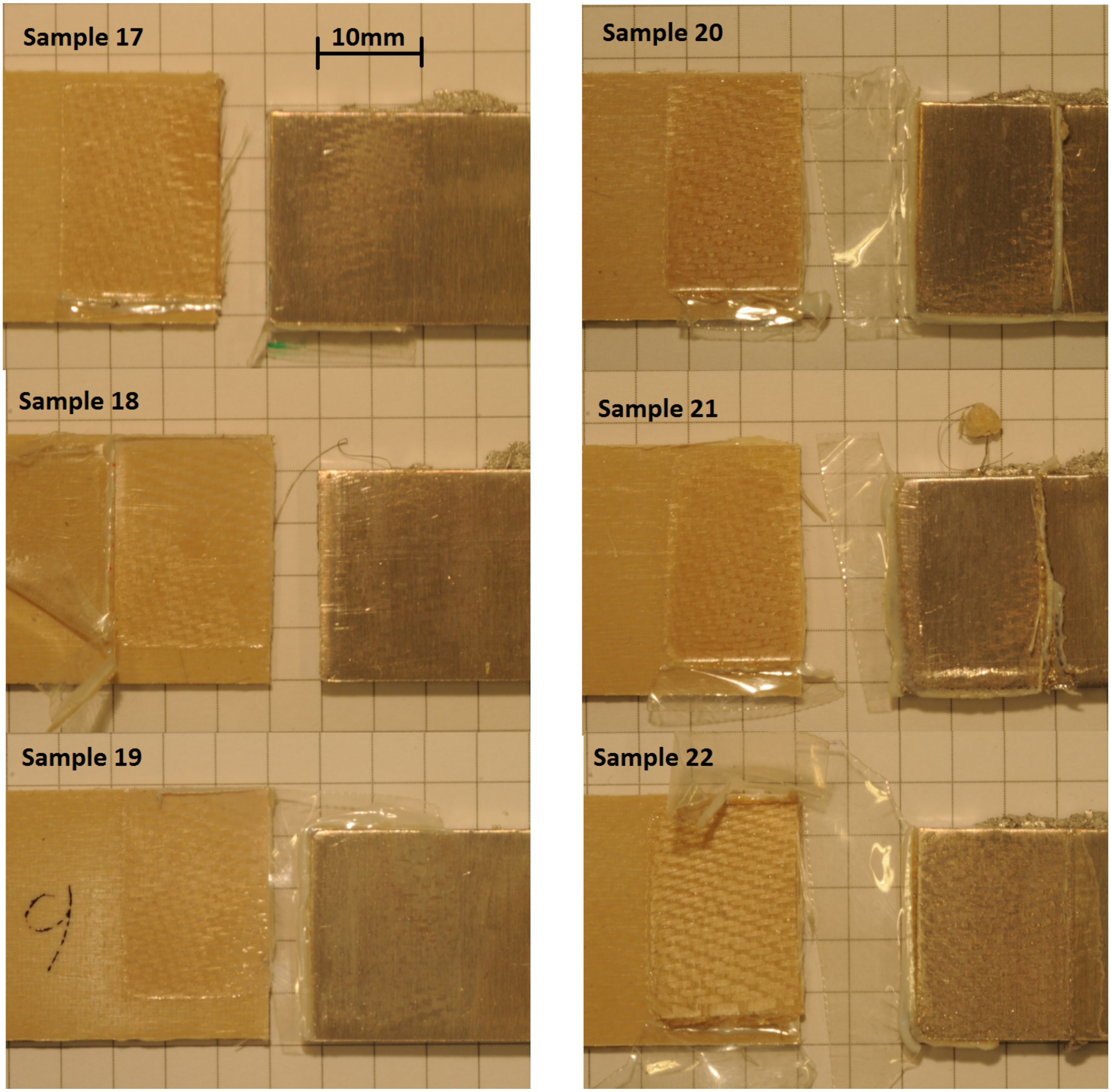

Figure B.3: Interface appearance of samples 17-22, series 3.

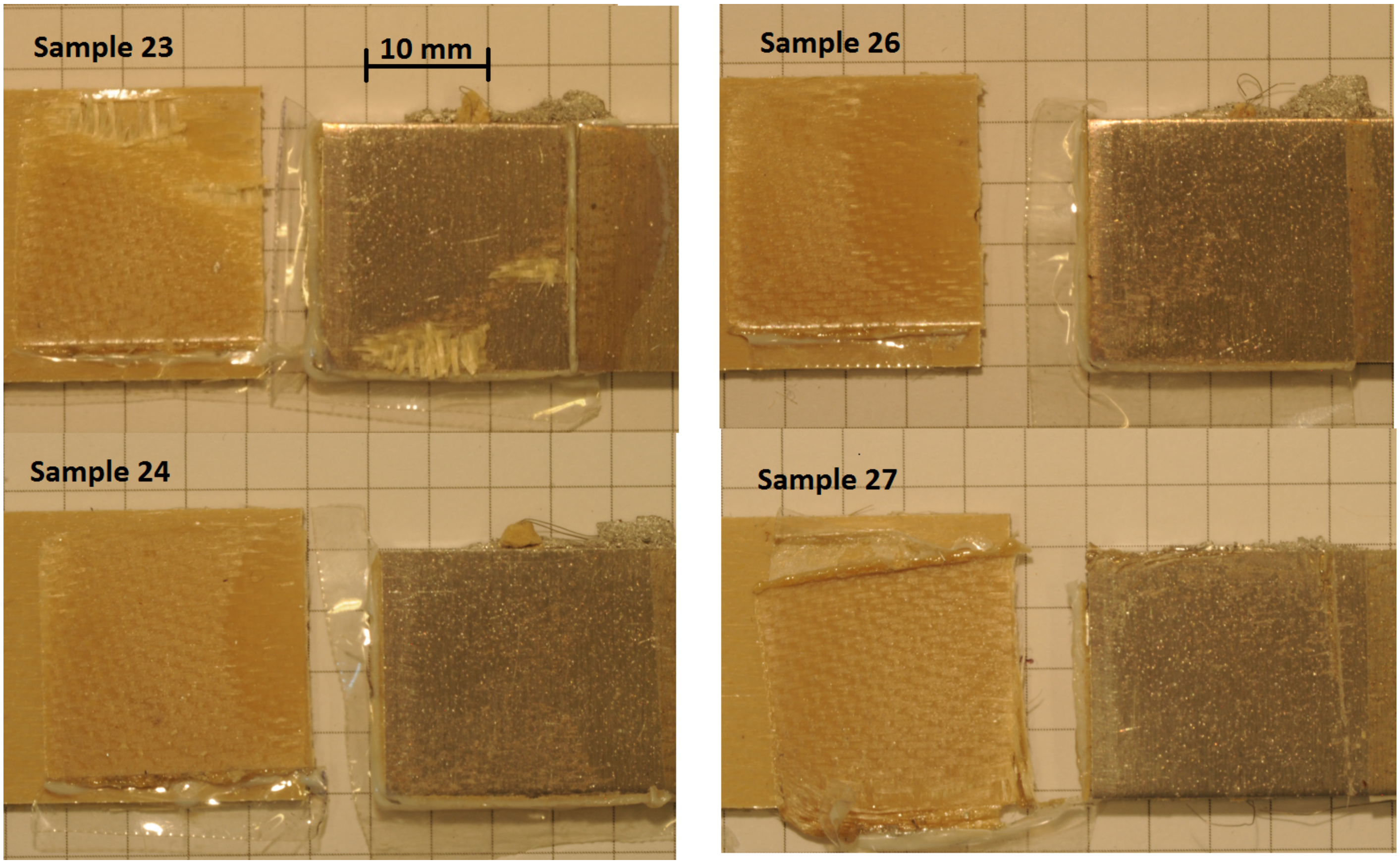

Figure B.4: Interface appearance of samples 23-27, series 4.