Execution and reliability of slip resistant connections for steel structures using CS and SS (SIROCO)

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Surface characterization of faying surfaces in slip factor tests for slip resistant bolted joints

Henrik Ahrman and Erik Schedin

Abstract

The faying surfaces from slip tests have been analyzed with optical and confocal microscopy. The work is part of WP6, Slip-resistant connections made of stainless steel plates and bolts in the RFCS project " Execution and reliability of slip resistant connections for steel structures using CS and SS (SIROCO)".
The roughness before slip testing as measured by the R_z-value is highest for the as-rolled 1D surface of 1.4404 followed by grit blasted and the shot blasted having the lowest R_z-values. The roughness of grit blasted surfaces is similar for all tested stainless steel grades (1.4003, 1.4404, 1.4162 and 1.4462).
The amount of isolated contact spots decreases and the amount of cold welds increases on faying surfaces from as rolled (1D) to shot blasted (SB) to grit blasted (GB). The friction factor increases in the same trend.
No significant difference in surface appearance of faying grit blasted surfaces can be seen for the different stainless steel grades and the friction factor shows no significant difference between the grades either.

Key words: Joints, bolts, surface roughness, cold welds, 1.4003, 1.4404, 1.4162, 1.4462, ferritic, austenitic, duplex

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1. Introduction

In the RFCS funded project "Execution and reliability of slip-resistant connections for steel structures using CS and SS"/SIROCO contract RFSR-CT-2014-00024 slip factor tests have been performed at University of Duisburg-Essen and at Institute for Metal and Lightweight Structures and Technical University of Delft, Stevin Laboratory. The tests aim at determining the critical load at which the joint starts to slip and from there calculate the critical slip factor for the joint. The critical slip factor is to be used to design a slip resistant bolted joint in a construction.

The aim of the SIROCO project is to determine the necessary technical data needed to update Eurocode and EN1090-2 to make design of slip resistant bolted joints possible for stainless steel. Today, this is only possible if the bolting procedure is qualified by the fabricator himself. There is a well-known "fact" in the construction community that stainless steel cannot be used in slip resistant bolted connections because of the tendency to creep at room temperature. The slip tests reported in this work is a part of the work to prove that stainless steel can very well be used in slip resistant bolted joints.

The slip factor test is a heavily instrumented test involving 4 load cells under the bolt heads and up to 12 extensometers to measure the slip in different positions of the joint, see Figure 1. The load cells are used both to secure the set clamping load and to measure the loss of preload during the test.

Figure 1 Outline of the slip factor test

2. Materials

The stainless steel grades included in SIROCO are ferritic 1.4003 (Outokumpu Moda 410L/4003), austenitic 1.4404 Outokumpu Supra 316L/4404), lean duplex 1.4162 (Outokumpu Forta LDX 2101) and duplex 1.4462 (Outokumpu Forta DX 2205). The plates were delivered in 8 mm (lap plates in Figure 1) and 16 mm (center plates in Figure 1) thickness. The mechanical properties of all plate materials are summarized in Table 1. All plates except 16 mm 1.4003 were delivered from Outokumpu.

The reason for the large difference in proof strength and tensile strength of plate 1 and 2 for 1.4003 is most probably due to some straightening action of plate 2. Both plates do fulfil the standard specification of 1.4003 according to EN ISO 10088-2.

Table 1 Mechanical properties of the plate materials

Stainless steel	grade	part	width [mm]	thickness [mm]	Rp0.2 [N/mm²]	Rm [N/mm2]	A5 %	HB	
Austenitic	1.4404	center	80	15.4	266	585	61%	-	
		lap		7.95	284	592	52%	168	
Ferritic	1.4003	center		16.3	338-341	513-520	25-26%	85	plate 1
					447-469	593-600	25%	82	plate 2
		lap		8.07	357-368	481-495	27-29%	77	
Lean Duplex	1.4404	center		15.2	544-560	725-730	34-37%	233-243	
		lap		8.65	570	730	38%	228	
Duplex	1.4462	center		15.4	538	788	34%	-	
		lap		8.06	632-644	709-714	33%	257	

The slip factor tests were performed with the as-delivered 1D surface of all plates, with shot blasted (SB) and with grit blasted (GB) surfaces. Shot blasting and grit blasting were performed by Institut für Korrosionsschutz Dresden GmbH.

3. Experimental technique

The analyses of the faying surfaces after the slip test focussed on one of the lap plates, see Figure 2 and were analysed with optical microscopy and confocal microscopy.

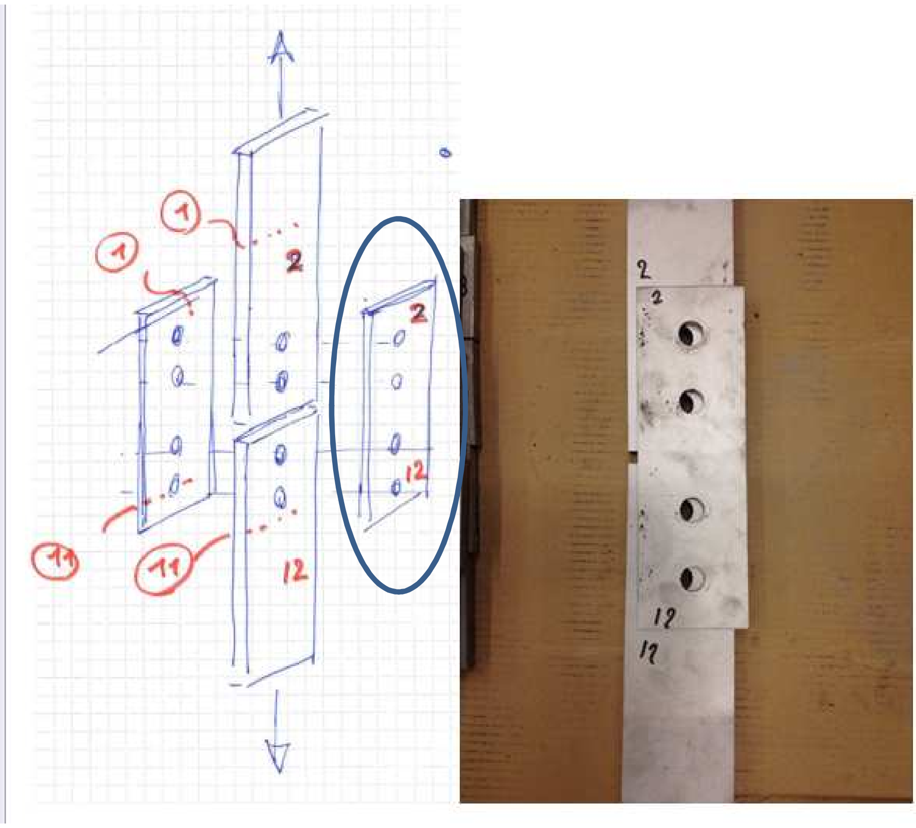


Figure 2 The surface analysis focussed on one of the cover plates

In [1] a prestudy was performed on utilization of confocal microscopy to analyse the faying surfaces after the slip test. In this work, a simplified procedure was adopted in order to be able to analyse a larger amount of faying surfaces. The so-called photorealistic view option was chosen at a magnification of 20 times. The confocal analysis focussed on two adjacent holes on the lap plates, while the optical analysis gave an overview of the faying surfaces.

4. Results

The surface roughness of the plates was measured with a mechanical stylus instrument before the tests both at University of Duisburg-Essen and at Technical University of Delft. Table 2 summarizes the result from University of Duisburg-Essen which coincides well with the results from Technical University of Delft. The as-received 1D surface has the highest R_z-values and the shot blasted surfaces the lowest values. The average values of grit blasted surfaces are within the scatter for all grit blasted plates indicating that there are just small differences in roughness between the different grades when grit blasted.

Table 2 Surface roughness of plate surfaces before the slip factor test (results from University of Duisburg-Essen)

	Lap plate		Center Plate	
Grade	Average R_z (µm)	Min Max	Average R_z (µm)	Min Max
1.4404, 1D	54	49	49	44
		59		53
1.4404, SB	35	31	38	36
		42		40
1.4404 GB	40	37	43	40
		44		47
1.4003, GB	45	41	47	46
		47		48
1.4462, GB	42	39	42	39
		49		46
1.4162, GB	47	39	37	36
		57		38

Figure 3 shows a typical overview of the faying surfaces. A dimpled surface to the right indicates cold welding areas, while this is not as evident on the more smoothed surface to the right.

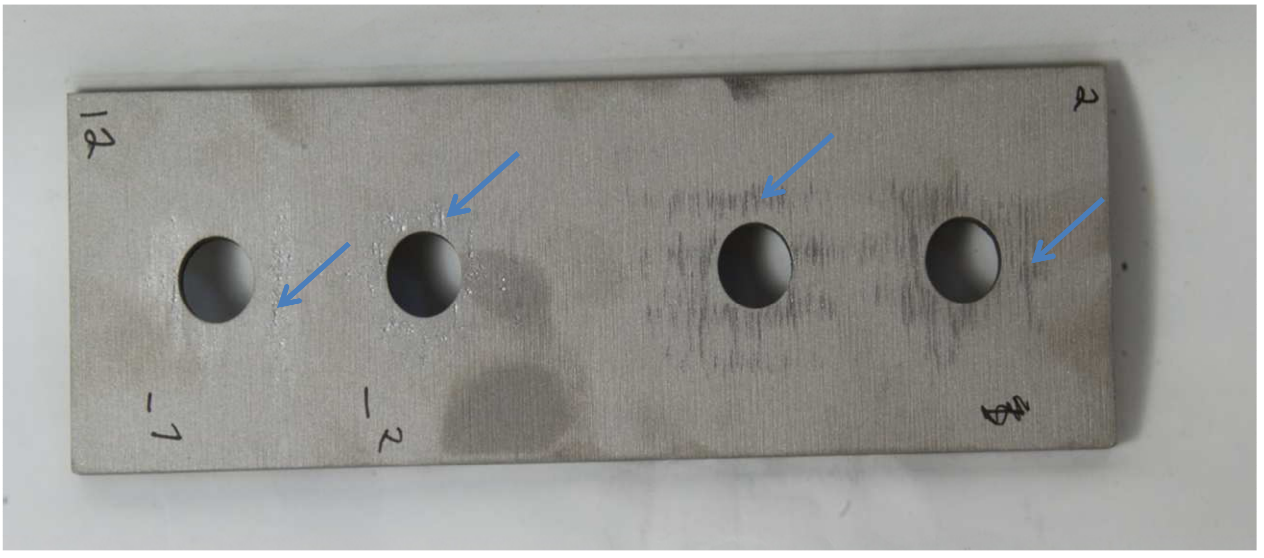


Figure 3 Overview of a typical lap plate after slip factor test showing a dimpled surface (blue arrows) to the left and smoothed areas to the right

A closer look in Figure 4 and Figure 5 reveals that both sides have the dimpled and the smoothed appearance (black arrows), while the dimpled features (blue arrows) are more clearly visible in Figure 4.

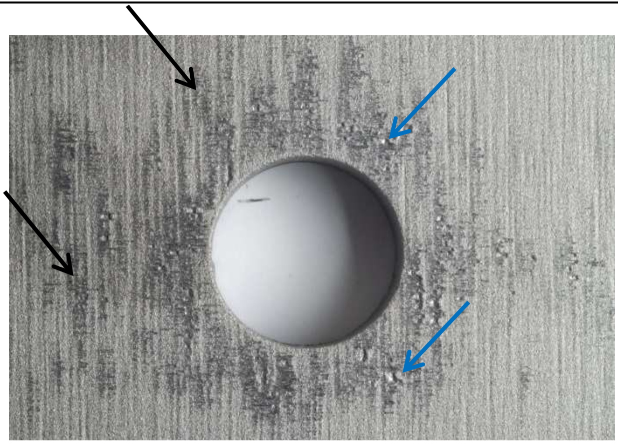


Figure 4 Close-up of the dimpled area in Figure 3

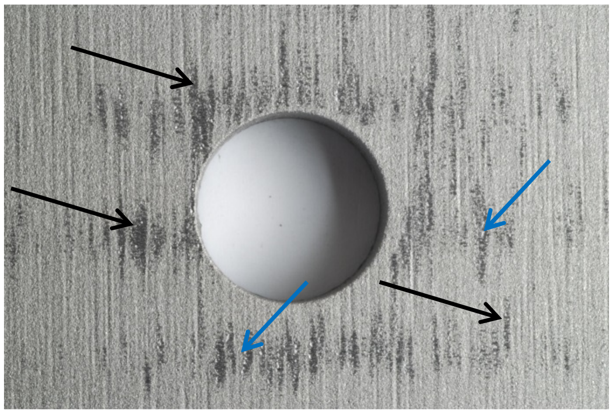


Figure 5 Close-up of the smoothed area in Figure 3

4.1 Comparison between different surface preparation techniques (all for 1.4404)

The faying surfaces for the as-received 1D surfaces (Figure 6) show flat and uniform contact spots (black arrows) on which sliding has occurred as demonstrated by the scratches (blue arrows). The shot blasted faying surfaces (Figure 7) are much rougher after sliding and the contact spots are not that evident, probably due to extensive cold welding (red arrows). The grit blasted faying surfaces (Figure 8) are even more destroyed with extensive cold welding (red arrows).

1D
Slip factor 0.21

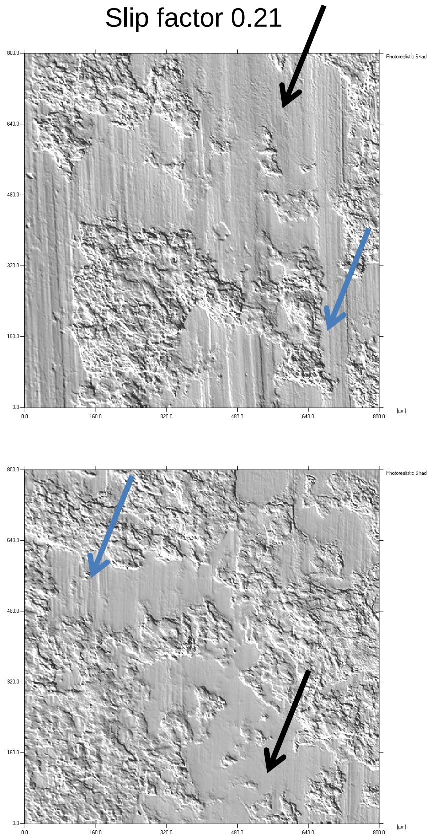


Figure 6 Faying surfaces in the dimpled area for 1D

SB
slip factor 0.27

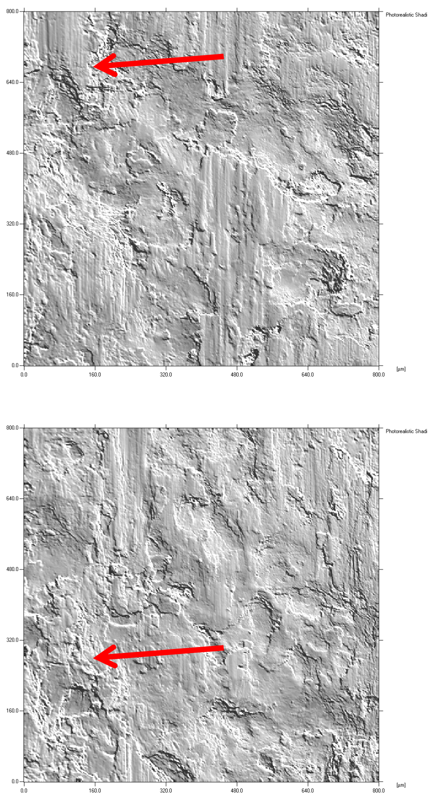


Figure 7 Faying surfaces in the dimpled area for SB

GB
slip factor 0.54

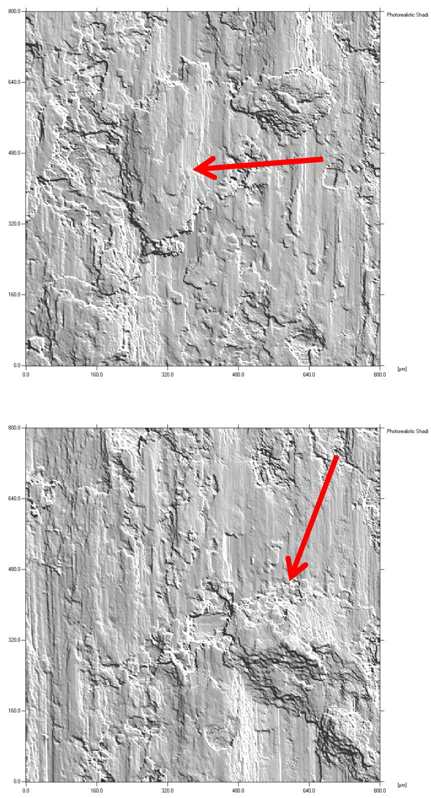


Figure 8 Faying surfaces in the dimpled area for GB

4.2 Comparison between the stainless steel grades (all for grit blasted surface preparation)

In the comparison between the different stainless steel grades samples from both laboratories were included. The main difference in testing condition between these two is that University of Duisburg-Essen used stainless steel bolts grade 1.4436 in 8.8 strength class, while Technical University of Delft used stainless steel bolts grade 1.4436 in 10.9 strength class. In Figure 9 to Figure 12 the upper surfaces are from University of Duisburg-Essen and the lower from Technical University of Delft.

The faying surfaces are heavily smeared out through cold welding and no actual difference between the grades can be seen.

1.4003

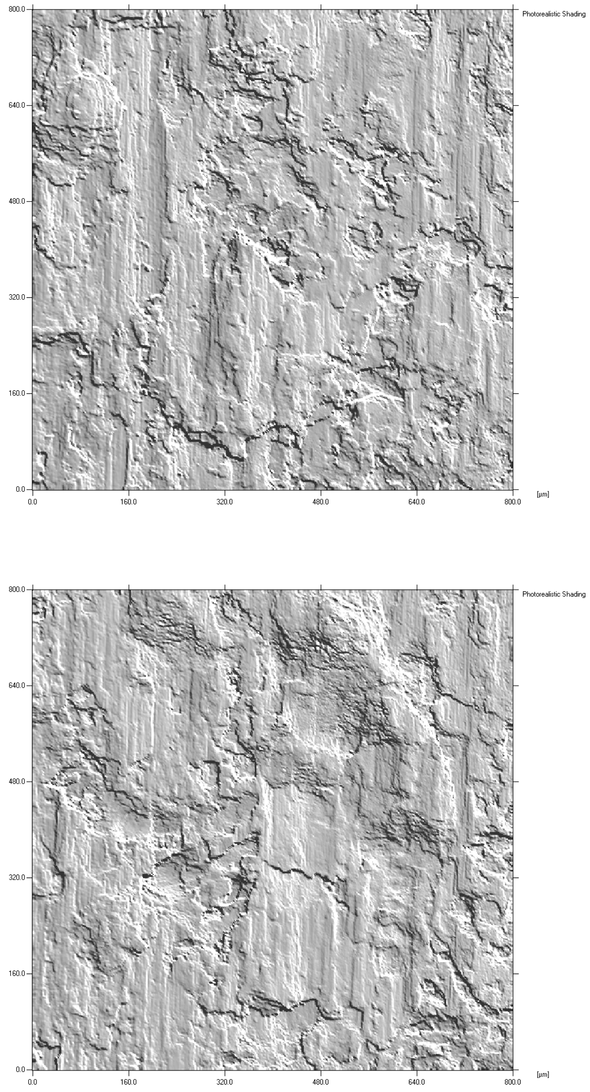


Figure 9 Faying surfaces in the dimpled area for 1.4003. Slip factor 0.61 for upper and 0.68 for lower.

1.4404

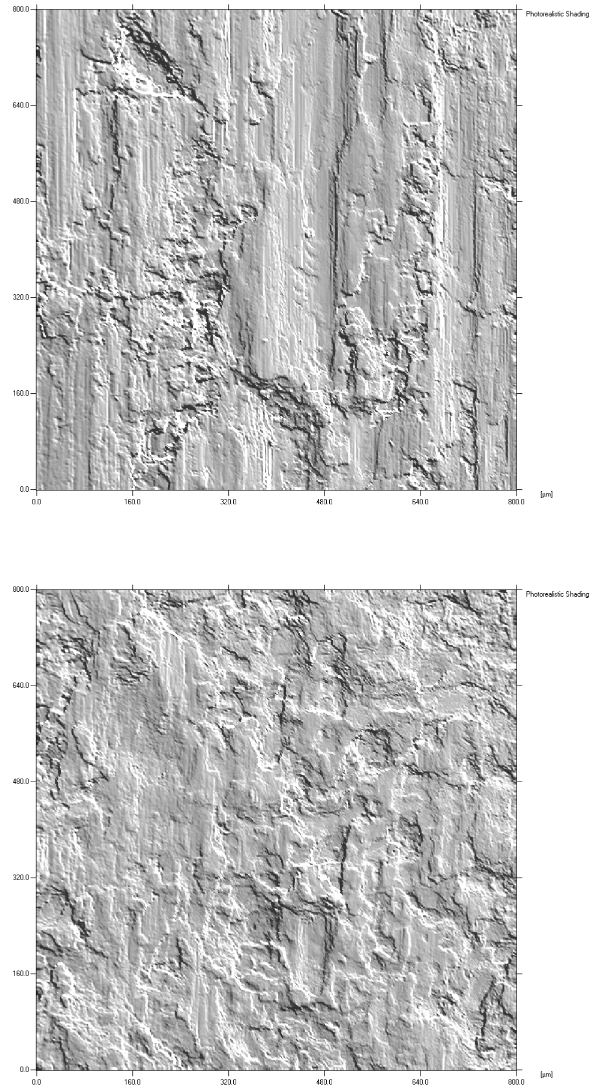
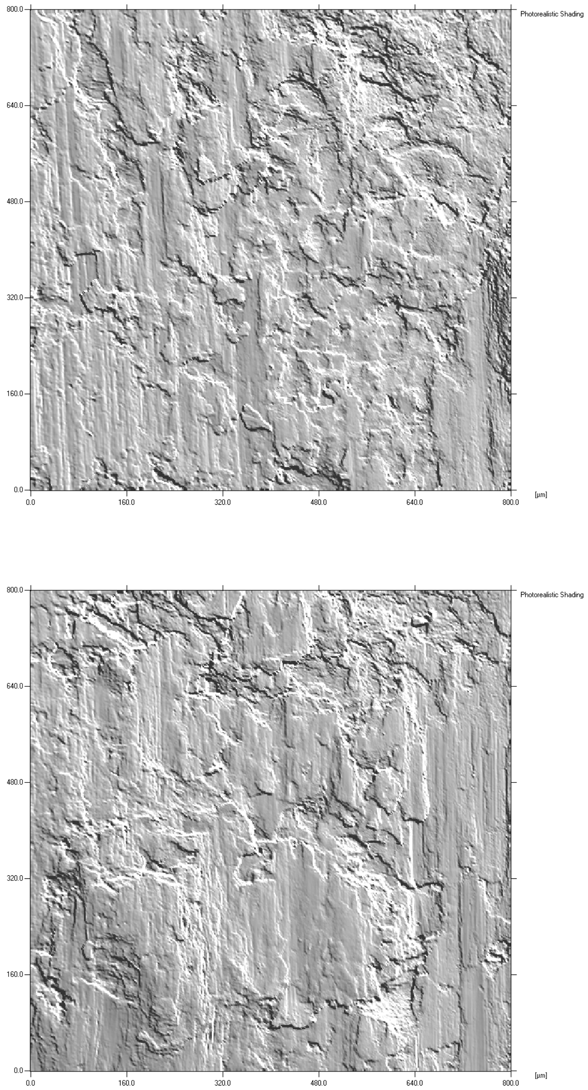


Figure 10 Faying surfaces in the dimpled area for 1.4404. Slip factor 0.54 for upper and 0.58 for lower.

1.4162



1.4462

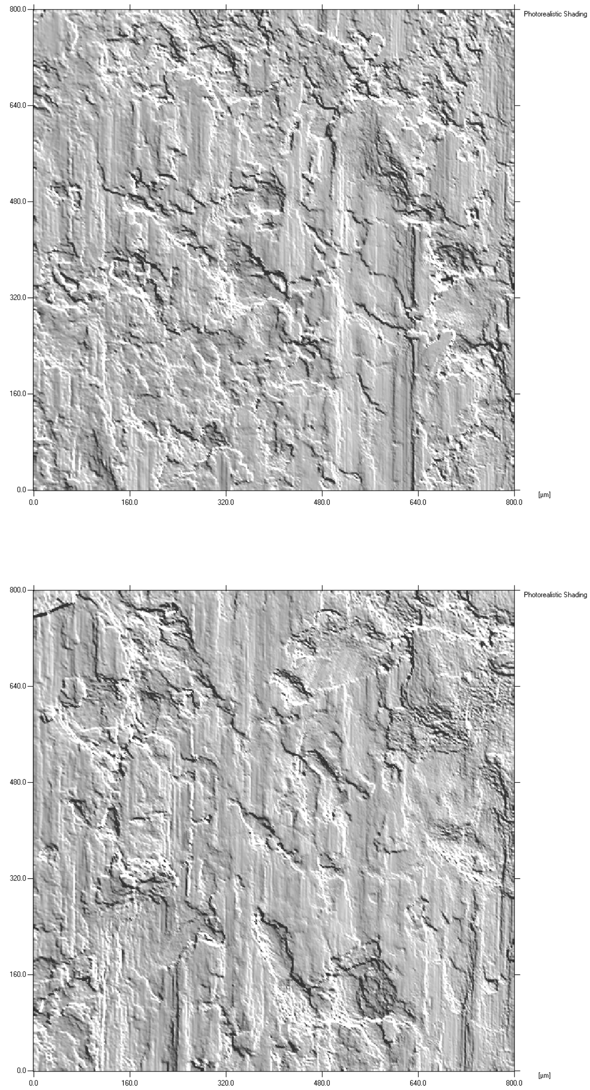


Figure 11 Faying surfaces in the dimpled area for 1.4162. Slip factor 0.53 for upper and 0.62 for lower.

Figure 12 Faying surfaces in the dimpled area for 1.4462. Slip factor 0.62 for upper and 0.68 for lower.

4.3 Comparison between dimpled and smoothed side (all for grit blasted surface preparation and tested by Technical University of Delft)

The comparison between the smoothed and dimpled areas in Figure 13 to Figure 16 indicates that the smoothed areas have more remains of the undestroyed contact spots (arrows), while the dimpled areas are heavily smeared out as previously stated. Among the different stainless steel grades 1.4462 seems to have less of the undestroyed contact spots in Figure 16. This is however more due to the chosen image area than typical for the grade.

1.4003
Slip factor 0.68

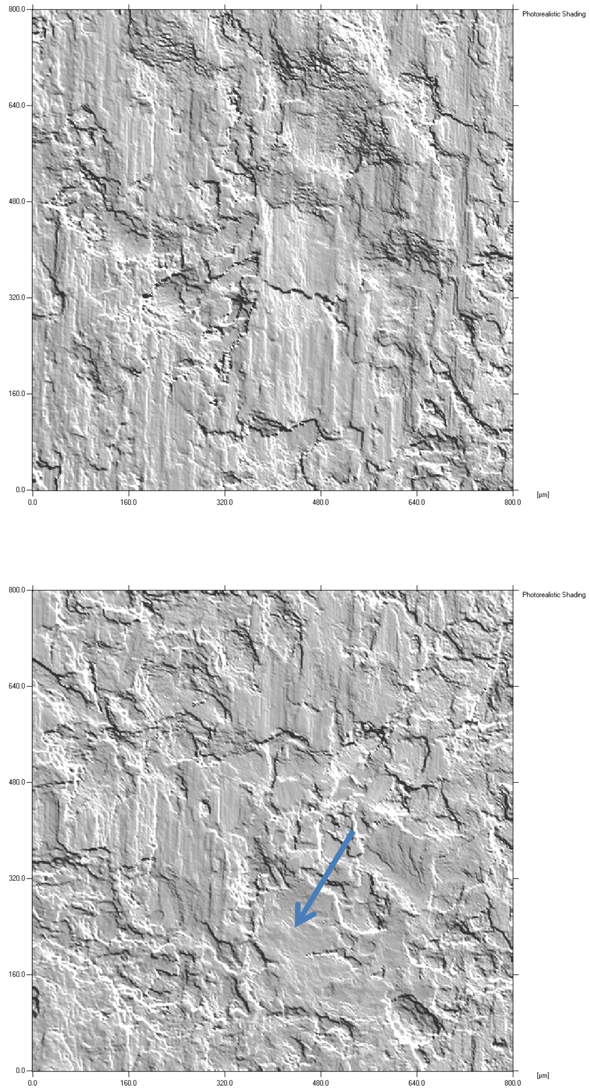


Figure 13 Faying surfaces in the dimpled (upper) and smoothed (lower) areas for 1.4003.

1.4404
Slip factor 0.58

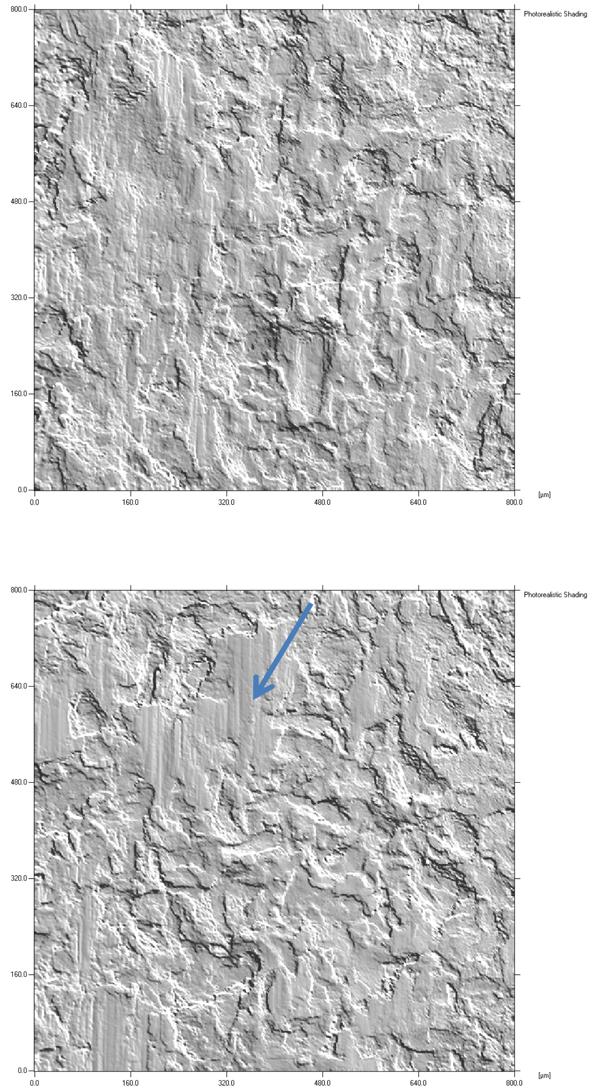


Figure 14 Faying surfaces in the dimpled (upper) and smoothed (lower) areas for 1.4404.

1.4162
Slip factor 0.62

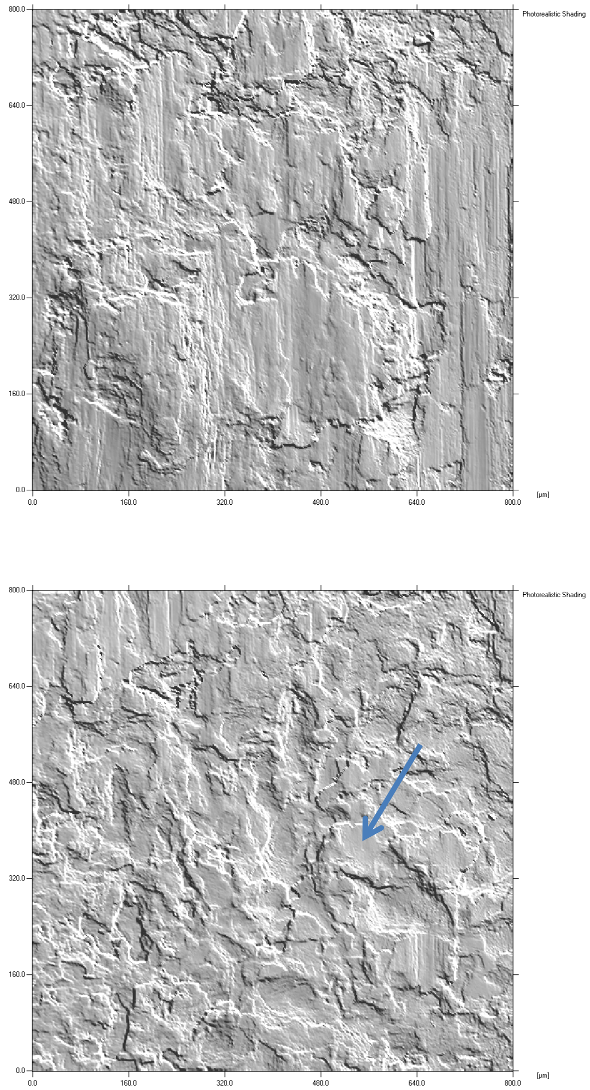


Figure 15 Faying surfaces in the dimpled (upper) and smoothed (lower) areas for 1.4162.

1.4462
Slip factor 0.69

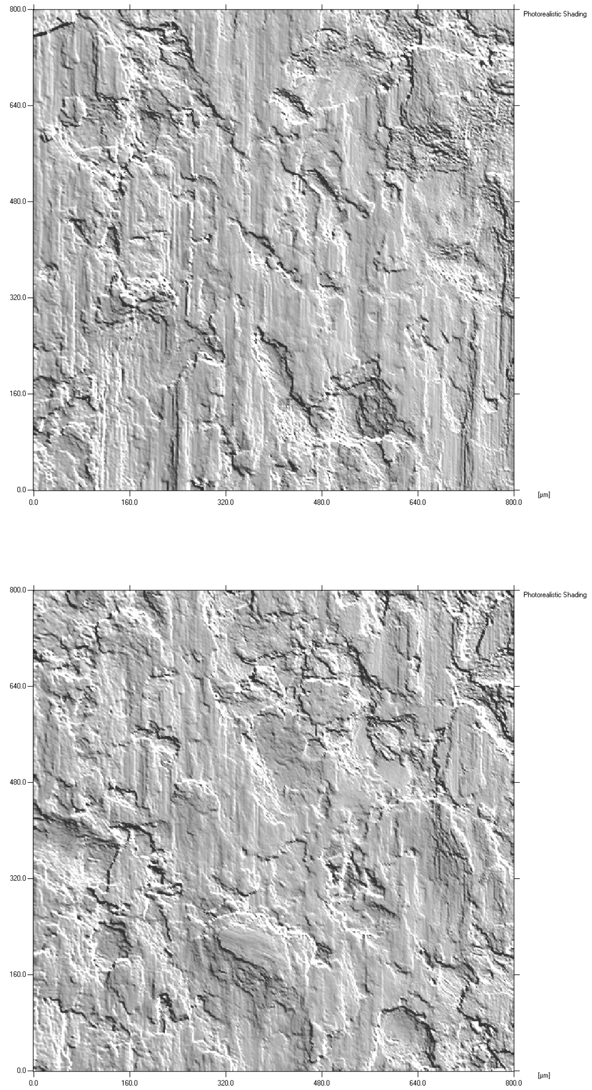


Figure 16 Faying surfaces in the dimpled (upper) and smoothed (lower) areas for 1.4462.

5. Conclusions

- The roughness before slip testing as measured by the R_z-value is highest for the as-rolled 1D surface of 1.4404 followed by grit blasted and the shot blasted having the lowest R_z-values.
- The roughness of grit blasted surfaces is similar for all tested stainless steel grades.
- The surface roughness of the faying surfaces varies on opposite sides of the test samples. Typically one side is more dimpled than the other smoother side. This can be related to more cold welds on the dimpled side for all stainless steel grades
- The amount of isolated contact spots decreases and the amount of cold welds increases on faying surfaces from as rolled (1D) to shot blasted (SB) to grit blasted (GB). The friction factor increases in the same trend.

- No significant difference in surface appearance of faying grit blasted surfaces can be seen for the different stainless steel grades and the friction factor shows no significant difference between the grades either.

6. Acknowledgments

Slip tests and surface roughness measurements were performed by Nariman Afzali at University of Duisburg-Essen and at Technical university of Delft under supervision of Peter de Vries

7. References

1 Liljedahl F. and Schedin E., Topography between contact surfaces in slip resistant bolted joint, Outokumpu internal report ARC20150180 and SIROCO extra deliverable D6.1