THE INFLUENCE OF SURFACE ROUGHNESS ON LOAD BEARING CAPACITY OF ADHESIVE JOINTS

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ABSTRACT

Experimental results on the effect of surface roughness on the adhesive joint strength have been presented in this paper. Mechanical properties of single lap adhesive joints with different surface roughness were tested and examined. Testing joints were made using two types of adherends: aluminium and stainless steel; and one type of adhesive: two component high-strength engineering adhesive. Good correlation was found between the theoretical knowledge and experimental results. It was also found that treating surfaces of soft materials like aluminium are significant different than treating materials like stainless steel, by means of surface roughness, because higher roughness diverse range could be reached.

1. INTRODUCTION

Good surface preparation is important to ensure optimum bond strength and reliable long-term performance of bonded joints, particularly under hostile service conditions [1,2]. Unsatisfactory surface preparation will result in premature and unpredictable bond failure at the adhesive/adherend interface. As a result, considerable effort is frequently expended in optimising the surface treatment.

Adhesives have a wide applicability and the adherends to which they are applied are also very diverse, both chemically and physically. An examination of the adherend surfaces reveals that when the molecular scale is approached, all engineering material surfaces are always rough [3]. Consequently, both the chemical and the physical nature of a surface are important in adhesion. It is often difficult to separate these two effects. The chemical nature influences the reactivity of the surface towards the adhesive. The surface energy and fundamental wetting characteristics also affect the strength and stability of adhesion.

2. PROBLEM STATEMENT

Many surface treatments that improve adhesion have the effect of roughening the surface involved. Treatments, such as abrasion and etching, also remove weak boundary layers, increase the reactivity of the surface, and improve its wetting behaviour. For efficient bonding, liquid adhesives need to be spread over the whole surface to be joined. The capillary forces play an important role in adhesive penetration into the surface crevices. The viscosity of the adhesive also plays an important role in its surface penetration behaviour.

For efficient bonding, care must be taken to ensure that the adhesive makes intimate contact with the adherend surface. The surface roughness can affect the spreading of the adhesive, either because the adhesive cannot penetrate the adherend or because it gels before it completes the penetration.

There have been attempts to model the effect of surface roughness on the contact angle with liquids. The best-known treatment is introduced by Wenzel [4]. Wenzel proposed a parameter ‘r’ to characterize a surface as follows:

$$r = \text{(total surface area)}/\ \text{(apparent geometric area)} \qquad (1)$$

Wenzel assumed that the value of r increased as the roughening increased. It is generally believed that the apparent contact angle decreases with increasing roughness values [5]. However, the wetting of a surface is a kinetic phenomenon and the liquid must first advance on the surface. Even if the ultimate equilibrium contact angle may be zero, the advancing contact angle is never zero but is a function of the rate of movement of the liquid. Not only the average roughness, but also the geometry of the adherend surface topographies is expected to affect the resulting joint strength [3].

As mentioned above, adhesion is the effect of various interaction forces in the adhesive layer between two adherends. It is obvious, therefore, that the quality of an adhesion depends not only on the chemical composition of the adhesive, but also on the chemical composition and, in particular, the surface condition of the materials to be bonded. Before discussing the influencing factors on the side of the adhesives, e. g. the molecular weight, branching, the type and number of polar or reactive groups, the terms of geometric, true, and effective surfaces should be defined first.

The geometric surface is the result of the plane dimensions and is an integral component of tensile strength values, which are indicated in Newton per square millimetre. The true surface is several times larger than the geometric surface as a result of the roughness: even on polished surfaces, unevenness of 10 to 100 nm have been measured. The effective surface is formed during wetting and is, therefore, the actual interface. It depends on the surface tension and the viscosity of the adhesive, and also on the structure (shape and size of the pores) of the surface. Although the size of the effective surface cannot be determined exactly, it must be smaller than the true surface, because as a rule, the pores and uneven parts of the surface are not completely filled by the adhesive. This assumption is also confirmed by the fact that bonds that have been set under pressure have higher adhesive strength: The pressure causes better wetting and consequently a more complete interfacial contact. It must also be pointed out that practically all surfaces exposed to the normal.

Single lap joints are investigated in this paper as a part of continuously testing of adhesive bonded joints. As was mentioned above, surface roughness has an influence on load bearing capacity of adhesive joints. In experimental part of the paper, the testing is focused on investigation of this influence in this type of joints. Stainless steel and aluminium was used as adherend materials, while the lap length was varied, and the thickness of adhesive layer was unchanged (0,15 mm).

3. EXPERIMENTAL RESEARCH

The standard single lap specimens for evaluating the load bearing characteristics i.e. strength of adhesively bonded joint have been prepared accordingly Fig. 1. Two types of adherends (materials to be bonded) have been considered; aluminium Al99.5 and stainless steel X5CrNi18-10. Dimensions of such prepared adherend plates were $a \times b \times s = 30 \times 90 \times 1{,}95$ mm (30×150×1,95 for PP 9.1-9.3 only*)*. The adherends are cleaned by an appropriate surface preparation method [7] (Fig. 2). The two-component epoxy adhesive *LOCTITE 3421* [7] is applied to the region to be lapped. The thickness of the applied adhesive is maintain at $\delta = 0{,}15$ mm by using an appropriate fixture device and allowed to cure to reach maximum strength (48 hours). The lap length has been varied in range from 15 to 60 mm for aluminium-epoxy joints, and 15 to 90 mm for stainless steel-epoxy joints.

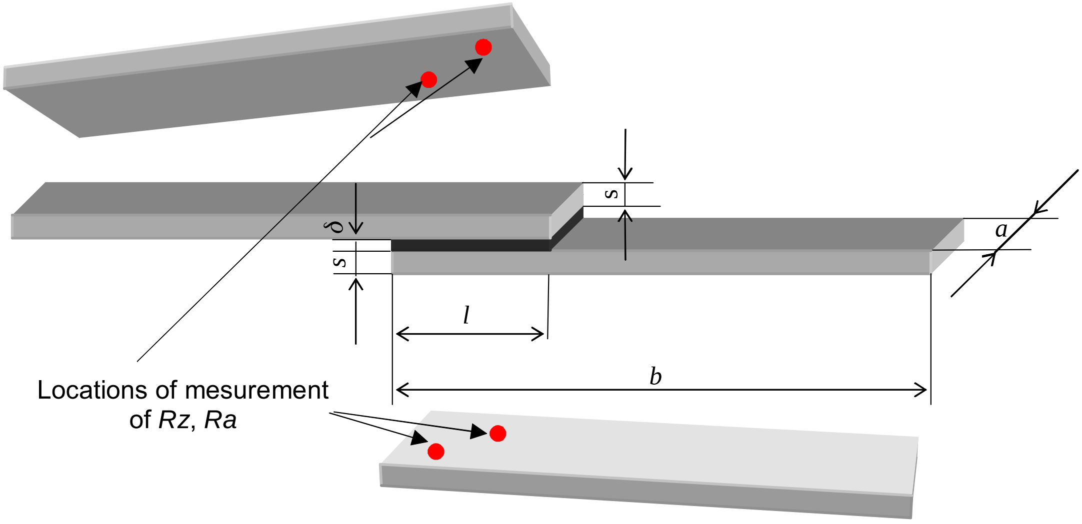


Figure 1. Single lap joint specimen

The all in this way prepared bonded joints have been stretched up to the break in the clamps of the tensile testing machine.

A Taylor-Hobson Surtronic 3+ perthometer was used to measure the surface roughness before bonding procedures. Locations of measurements are shown on Fig. 1. Two measurements are performed in every part prepared for bonding. Surface roughness was both measured before and after preparing (grinding and degreasing with *Loctite 7061*) for bonding.

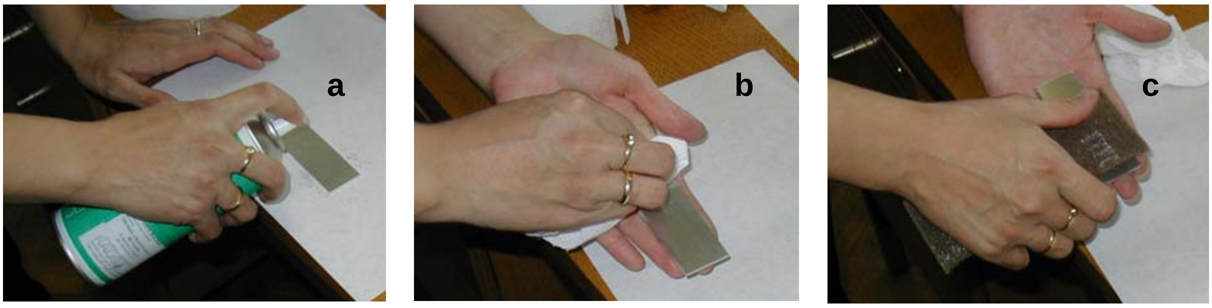


Figure 2. Degreasing (a,b) and grinding (c) of plates

The arithmetic mean roughness, *Ra* value, was used for comparison purposes. When finished with scanning, the *Ra* value was read off from the display of the instrument. The ‘arithmetic mean roughness’ is defined as follows

$$Ra = \frac{1}{L_m} \int_{x=0}^{x=L_m} |y| dx \tag{2}$$

where L_m is the total scanned length in the x (horizontal) direction (Fig. 3).

The Taylor-Hobson perthometer also provides ‘mean peak-to-valley height’, *Rz*, values. The *Rz* value is the arithmetic mean from the peak-to-valley heights of five successive sampling lengths (Fig. 4).

All the samples were tested at average displacement rate of jaws 0,2 mm/min, with an Carl Schenck AG 1000 kN tensile testing machine. Epsilon extensometer was used with a gage length of 25 mm to measure joints strains. Once all the samples had been tested, the load data from the data acquisition computer were stored on a diskette for data analysis.

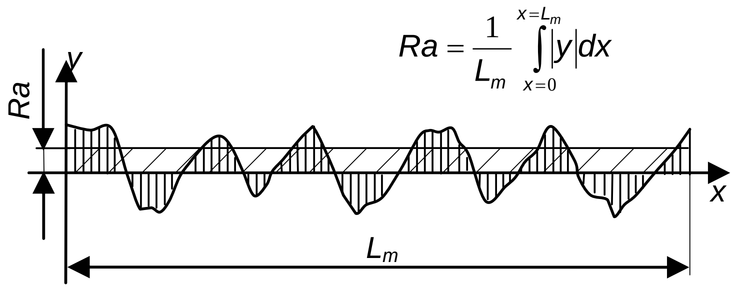
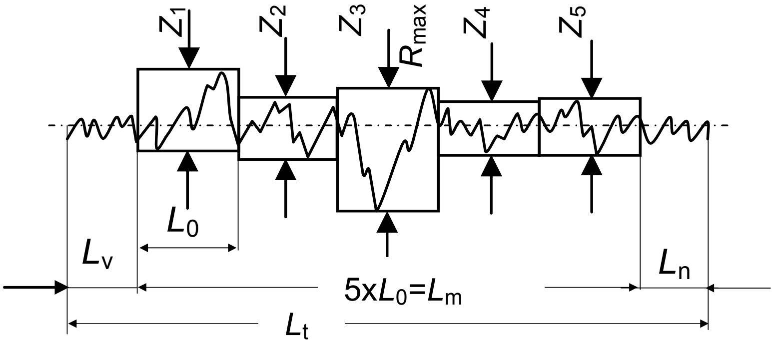


Figure 3. Calculation of the average surface roughness Ra [3]



$$Rz = \frac{1}{5}\left(z_1 + z_2 + z_3 + z_4 + z_5\right)$$

Figure 4. Calculation of the mean roughness depth Rz [3]

4. RESULTS AND DISCUSSION

The results of both surface roughness for untreated and for treated (grinding and degreasing with *Loctite 7061*) specimens are shown in table 1 (aluminium plates measuring) and 2 (stainless steel plates measuring).

Table 1. Results of surface roughness measuring before bonding (specimens are made of aluminium)

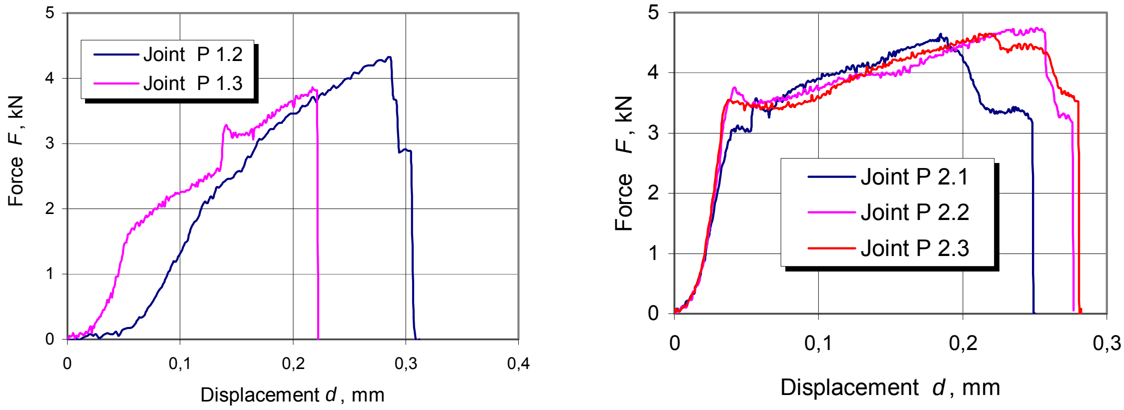
Specimen mark	a				b			
	Ra, µm		*Rz*, µm		*Ra*, µm		*Rz*, µm	
	1	2	1	2	1	2	1	2
P 1.1	0,92	1,06	5,8	6,9	1,16	1,46	7,5	8,6
P 1.2	1,50	0,88	10,6	6,3	1,18	1,06	8,3	6,8
P 1.3	1,46	1,1	8,4	7,3	1,12	1,24	8,3	8,4
P 2.1	0,98	1,30	7,3	10,9	1,34	1,96	10,3	13,4
P 2.2	1,10	0,98	9,9	7,3	1,26	1,10	9,5	8,5
P 2.3	1,06	1,80	6,8	14,2	1,08	1,46	7,8	8,7
P 3.1	0,52	0,52	3,0	2,6	1,18	0,92	6,1	7,5
P 3.2	1,28	0,54	6,0	4,0	0,58	0,62	4,0	3,9
P 3.3	0,46	0,46	3,9	3,6	1,54	0,48	9,5	3,2
P 4.1	0,66	0,48	4,3	3,7	0,82	0,60	4,5	3,8
P 4.2	0,44	0,68	3,8	5,3	0,60	0,56	4,6	3,6
P 4.3	0,74	1,02	4,9	8,1	0,73	1,02	5,1	7,8
P 5.1	0,96	0,90	7,6	6,9	0,84	0,96	6,8	7,0
P 5.2	1,02	0,88	6,4	6,7	1,08	0,92	7,2	7,5
P 5.3	1,14	1,26	7,8	9,7	0,98	1,22	5,8	8,7
Mean value	0,949	0,924	6,433	6,900	1,033	1,039	7,020	7,160
Before treatment: *Ra* = 0,19 µm; *Rz* = 1,8 µm								

Table 2. Results of surface roughness measuring before bonding (specimens are made of stainless steel)

Specimen mark	a				b			
	Ra, µm		*Rz*, µm		*Ra*, µm		*Rz*, µm	
	1	2	1	2	1	2	1	2
PP 1.1	0,42	0,42	3,4	3,2	0,74	1,38	3,7	3,8
PP 1.2	0,34	0,38	2,5	3,1	2,28	0,84	10,4	5,3
PP 1.3	0,30	0,54	2,4	3,7	0,42	3,32	4,0	4,3
PP 1.4	0,51	0,46	3,71	3,52	0,46	0,42	3,43	3,13
PP 1.5	0,35	0,38	2,81	3,06	0,32	0,26	2,41	1,94
PP 2.1	0,38	0,41	2,26	2,69	0,40	0,48	2,94	3,33
PP 2.2	0,34	0,32	2,72	2,51	0,39	0,32	2,93	2,28
PP 2.3	0,32	0,26	2,33	1,72	0,29	0,39	2,31	2,64
PP 2.4	0,36	0,32	2,66	2,57	0,44	0,44	3,41	3,34
PP 2.5	0,32	0,28	2,77	1,81	0,29	0,32	2,15	2,01
PP 3.1	0,44	0,49	3,72	3,73	0,40	0,45	2,98	3,14
PP 3.2	0,50	0,39	4,05	3,06	0,41	0,43	2,90	3,12
PP 3.3	0,38	0,38	2,78	2,62	0,38	0,34	2,63	2,73
PP 3.4	0,29	0,26	2,39	1,80	0,37	0,42	2,70	3,17
PP 3.5	0,44	0,42	3,57	2,86	0,28	0,33	2,32	2,71
PP 4.1	0,28	0,26	2,40	2,16	0,38	0,41	2,65	3,23
PP 4.2	0,36	0,29	3,10	1,98	0,48	0,32	3,58	3,04
PP 4.3	0,29	0,30	2,04	2,26	0,45	0,47	3,19	2,84
PP 4.4	0,23	0,23	1,94	1,64	0,23	0,27	1,90	2,03
PP 4.5	0,41	0,45	2,78	3,25	0,29	0,34	2,06	2,66
PP 5.1	0,28	0,30	2,26	2,45	0,36	0,35	2,74	2,31
PP 5.2	0,26	0,22	1,99	1,71	0,34	0,38	2,72	2,97
PP 5.3	0,31	0,38	2,15	2,70	0,34	0,51	2,66	3,35
PP 5.4	0,22	0,23	1,54	2,26	0,29	0,42	2,45	2,93
PP 5.5	0,27	0,25	2,22	2,17	0,34	0,26	2,51	1,89
PP 6.1	0,27	0,31	2,03	2,21	0,51	0,30	3,52	2,17
PP 6.2	0,32	0,27	2,45	2,17	0,31	0,27	1,89	1,87
PP 6.3	0,31	0,24	2,07	1,90	0,28	0,36	2,15	2,68
PP 6.4	0,36	0,47	2,48	2,96	0,30	0,23	2,00	1,67
PP 6.5	0,36	0,23	2,15	1,80	0,30	0,42	2,30	3,12
PP 7.1	0,29	0,27	2,61	2,16	0,34	0,22	2,16	1,72
PP 7.2	0,31	0,28	2,32	2,01	0,33	0,37	2,41	3,13
PP 7.3	0,28	0,33	2,43	2,30	0,36	0,27	2,56	2,45
PP 7.4	0,29	0,27	2,08	1,96	0,34	0,30	2,94	2,56
PP 7.5	0,28	0,44	2,24	3,19	0,32	0,29	2,36	2,19
PP 9.1	0,16	0,17	1,28	1,26	0,15	0,17	1,30	1,22
PP 9.2	0,21	0,18	1,78	1,50	0,15	0,20	1,22	1,60
PP 9.3	0,20	0,20	1,49	1,72	0,16	0,17	1,32	1,36
Mean value	0,322	0,323	2,471	2,412	0,400	0,459	2,784	2,682
Before treatment: *Ra* = 0,32 µm; *Rz* = 1,8 µm								

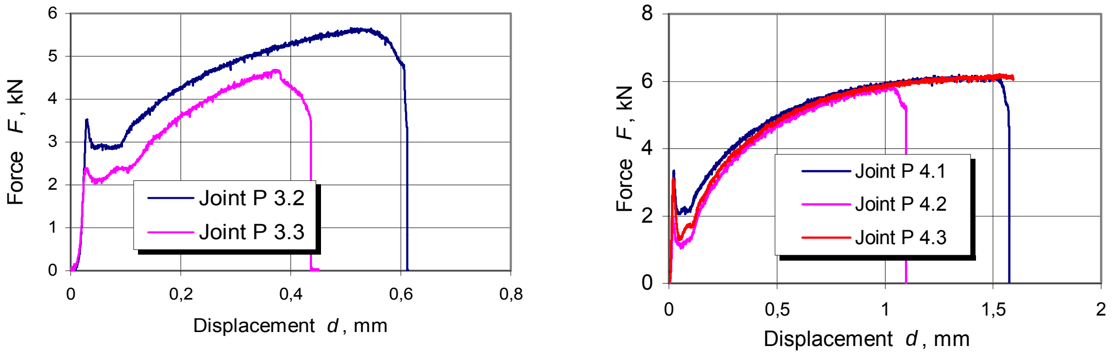
The average surface roughness values for the untreated aluminium plates are *Ra*=0,19µm, *Rz* = 1,8 µm; and after treating *Ra*=0,986µm, *Rz* = 6,878 µm. The average surface roughness values for the untreated stainless steel plates are *Ra* = 0,32 µm;

Rz=1,8μm, and after treating *Ra* = 0,376 μm, *Rz*=2,587 μm. From the measured results it is obviously that the difference between surface roughness before and after treating for aluminium is more striking. This leads to the conclusion that preparing of soften materials like aluminium has more moment on surface roughness values, which is in correlation with forces transferred crossover the joints. As can be seeing from results presented for stainless steel, those differences are minimal. Preparing of surfaces with goal to increasing *Ra* and *Rz* has not that much effect. Figure 5 shows the results of tensile testing of prepared joints for aluminium-epoxy combination and for all values of lap length.



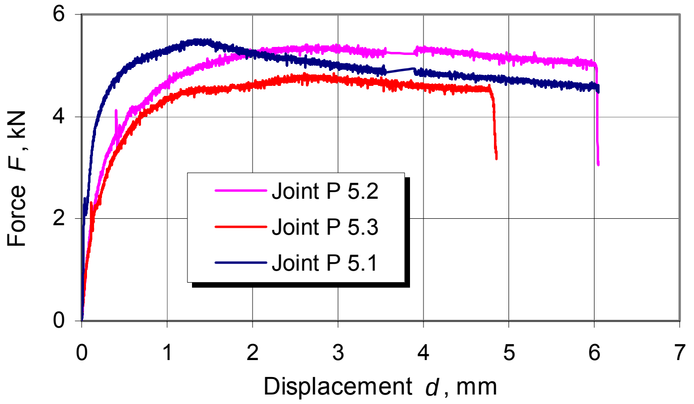
a) lap length is 15 mm

b) lap length is 20 mm



c) lap length is 30 mm

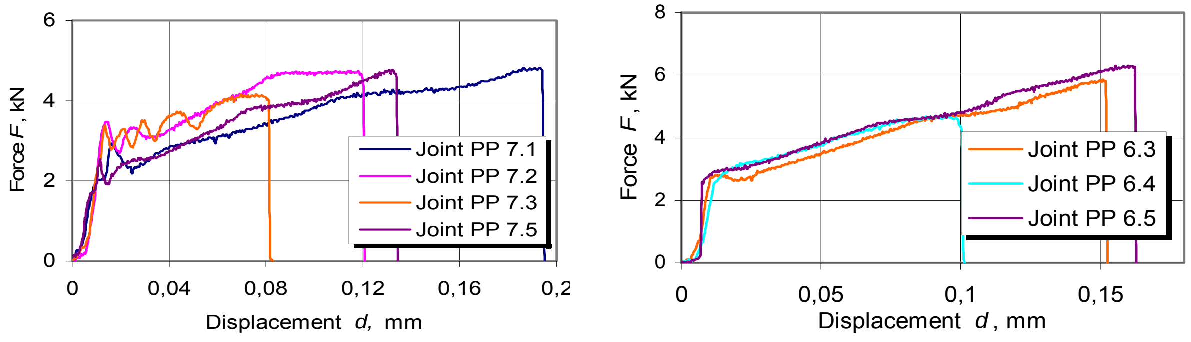
d) lap length is 40 mm



e) lap length is 60 mm

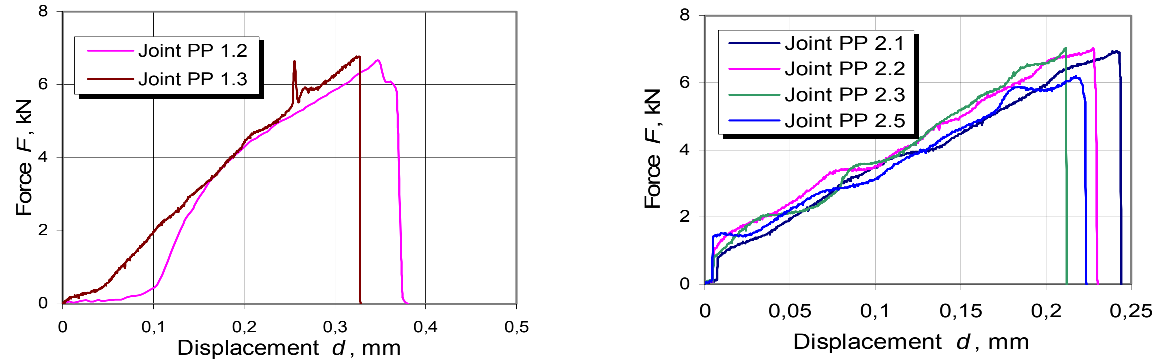
Figure 5. Experimental results of specimens tensile testing: adherend material is aluminium

Figure 6 shows the results of tensile testing of specimens for stainless steel-epoxy combination and for all values of lap length.



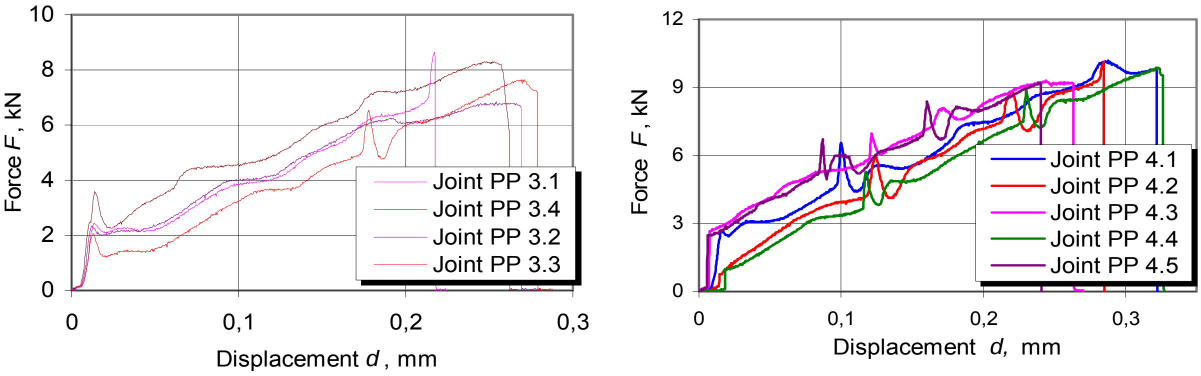
a) lap length is 6 mm

b) lap length is 10 mm



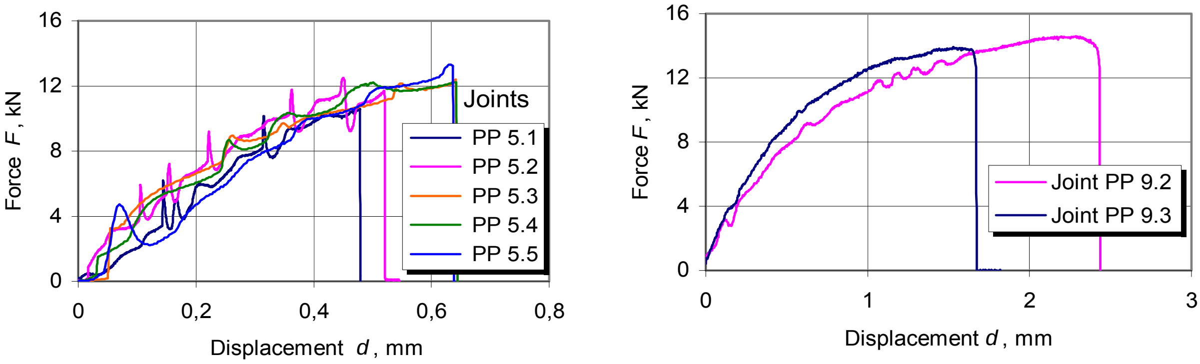
c) lap length is 15 mm

d) lap length is 20 mm



e) lap length is 30 mm

f) lap length is 40 mm



g) lap length is 60 mm

h) lap length is 90 mm

Figure 6. Experimental results of specimens tensile testing: adherend material is stainless steel

The adhesive shear strength (τ_a) has been calculated as a maximum shear stress achieved in an adhesive layer, based on recorded maximum tensile forces for each tested joints:

$$\tau_a = \frac{F_{\max}}{l \cdot a} \tag{3}$$

and a joint tensile strength (σ_s) as a maximum tensile stress transferred crossover the joint:

$$\sigma_s = \frac{F_{\max}}{s \cdot a} \tag{4}$$

Figure 7 presents relations between *Rz* and *Ra* parameters for both of materials used as adherend. It can be seeing that the *Rz* values are approximately seven times higher than *Ra* values.

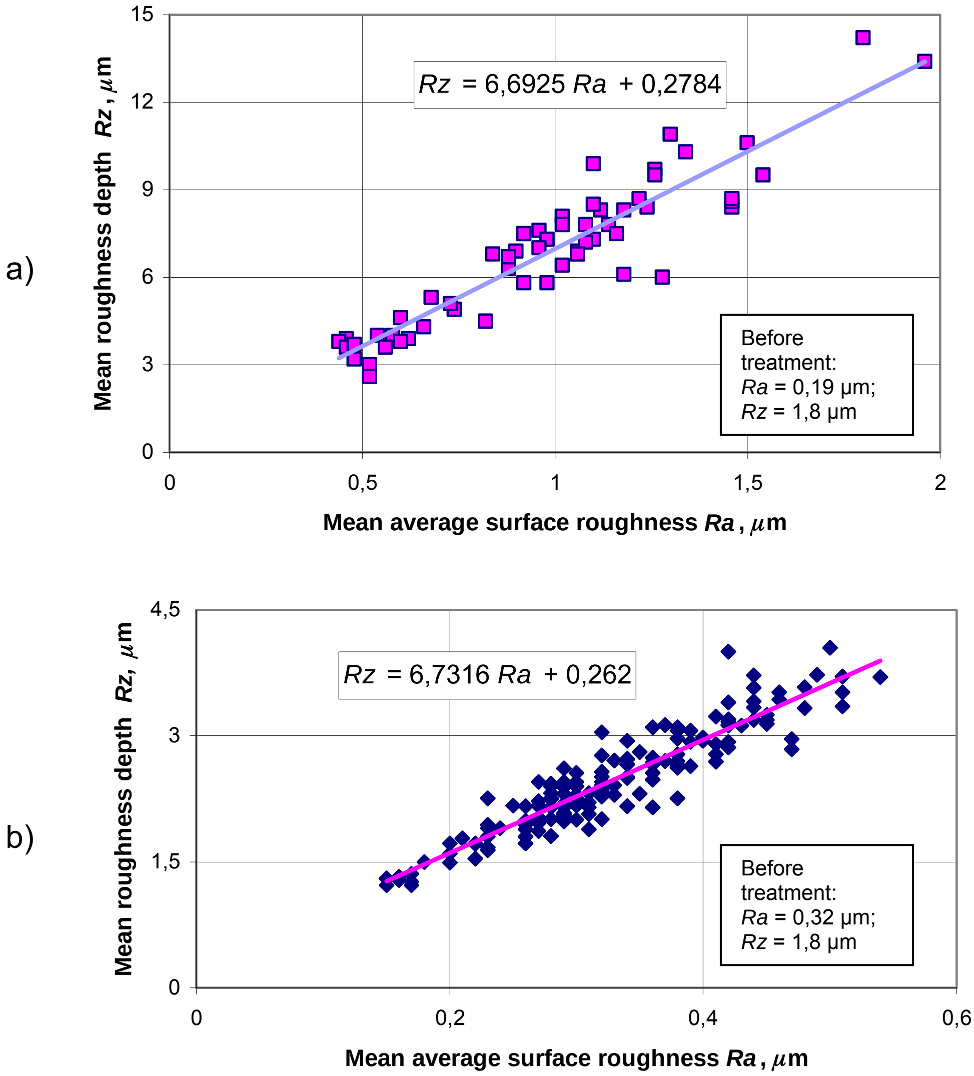


Figure 7. Experimental results of surface roughness measuring; adherend material is a) aluminium; b)stainless steel

Load-bearing capacities of the bonded joint are shown by joint tensile strengths values calculated by using the equation (4). The figure 8 presents the influence of surface roughness on joint tensile strength for aluminium as adherend. Analysis of results gives a following note: surface roughness doesn't have significant influence on achieved values of joint tensile strength at given lap length (Fig. 8 and 9: a, b).

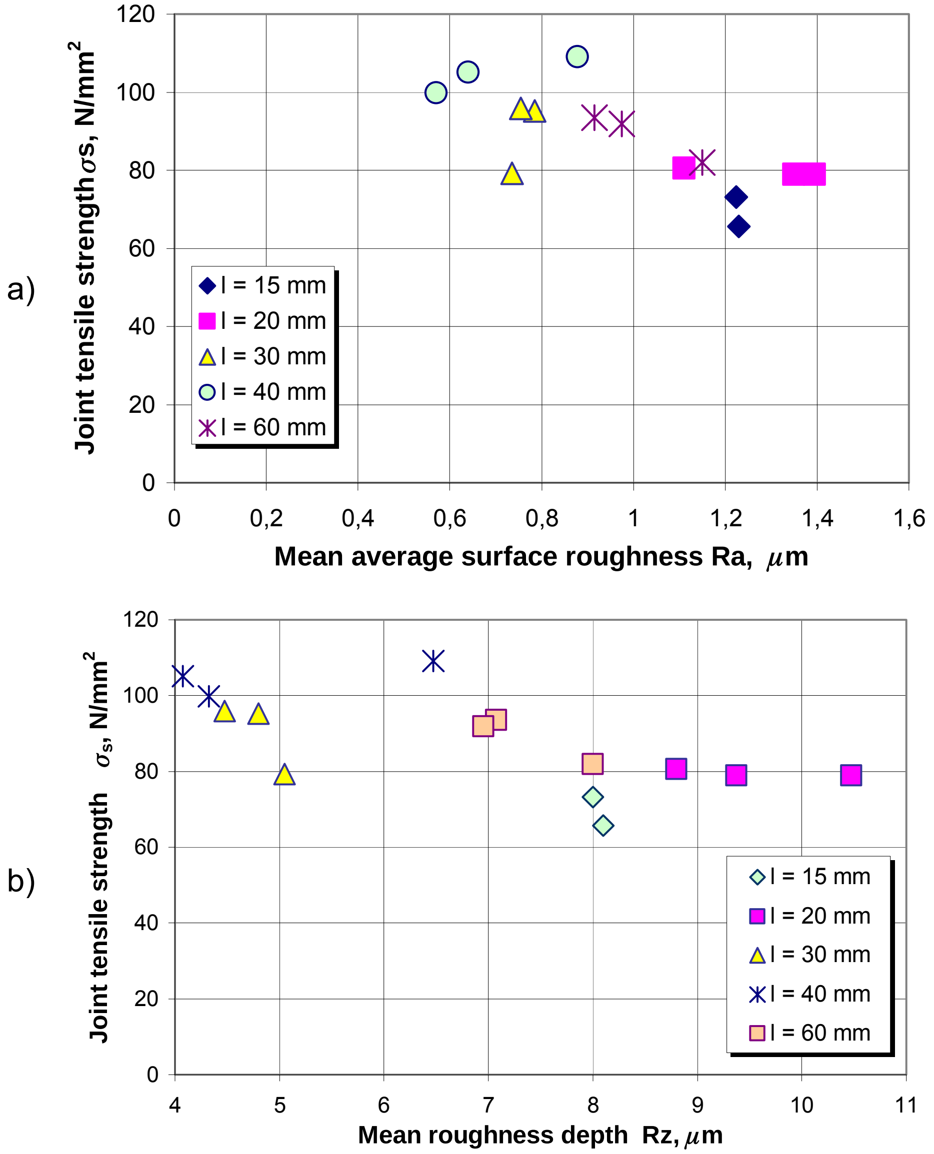


Figure 8. Joint tensile strength vs. surface roughness (adherend material: aluminium)

For every group of results for the same lap length, it could be drawn straight line parallel with abscissa. Every line would present the strength value for group of specimens. With this approach it can be seeing that different values of surface roughness in observed interval lead to the same values of joint strength at given lap length.

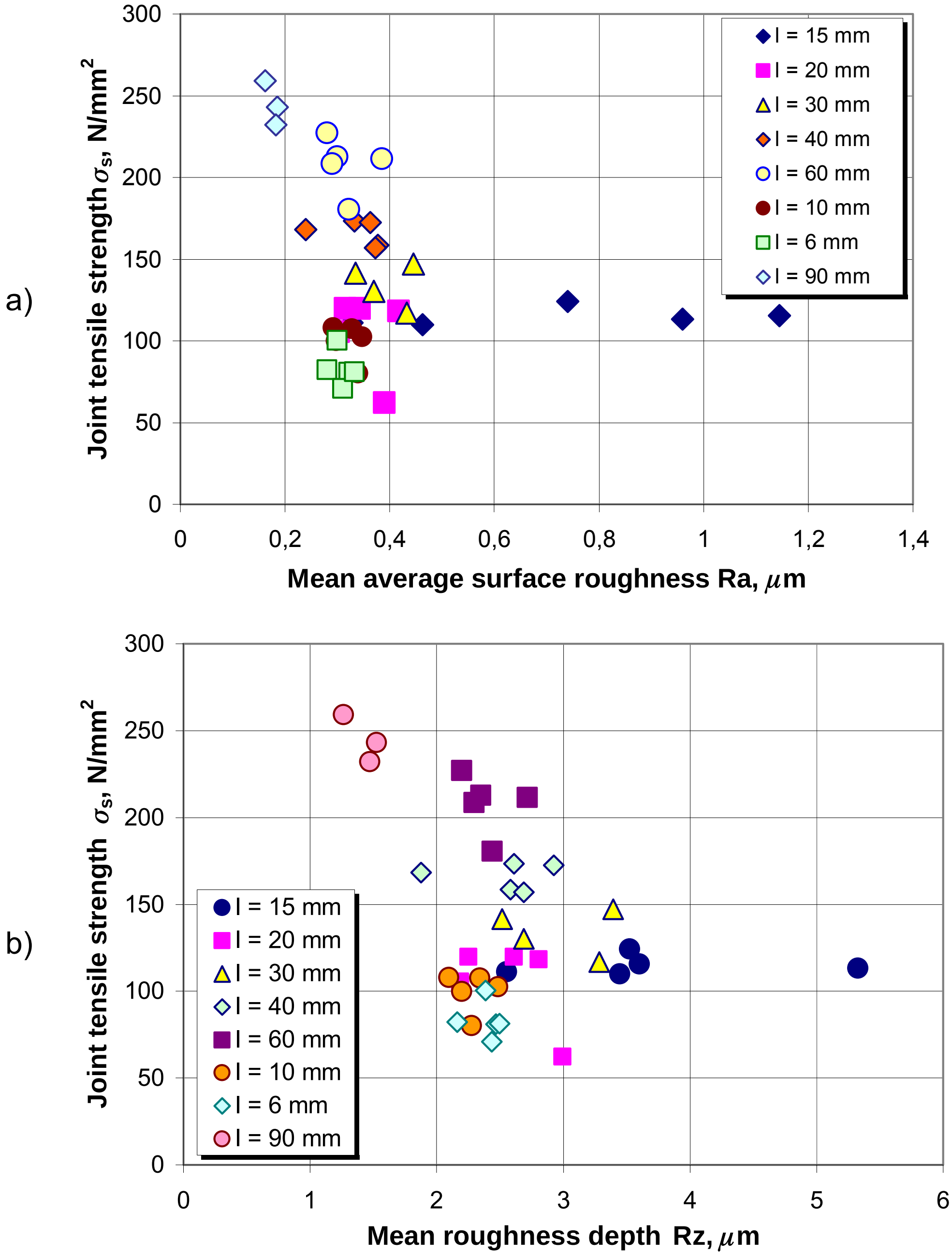


Figure 9. Joint tensile strength vs. surface roughness (adherend material: stainless steel)

For joints with aluminium as adherend material *Ra* was measured from 0,6 to 1,4 μm, respectively. Comparing the recommended range (0,8 to 3,2 μm) [8] of surface finishing, with values of surface roughness parameters reached during experimentation one can conclude that they are in good correlation. The similar fact arises for *Rz*: measured values are 4 to 10,5 μm, respectively, and recommended are 6 to10 μm [8].

The same approach goes for analysing of surface roughness influence on stainless steel as adherend (fig. 9). Measured values of *Ra* was from 0,15 to 0,5 μm, and of *Rz* from 1,5 to 3,5 μm, respectively. For hard materials like this one, preparing with grinding doesn't give a higher values of surface roughness parameters (before treating *Ra* was 0,32 μm, and *Rz* was 1,8 μm), so it can be conclude that preparing of soften materials results with higher diverse of roughness and it seems with no significant influence on tensile strength Figs. 8 and 9.

5. CONCLUSIONS

Quality of joint surface preparation is important to ensure optimum bond strength and reliable long-term performance of bonded joints. Unsatisfactory surface preparation will result in premature and unpredictable bond failure at the adhesive/adherend interface. As a result, considerable effort is frequently expended in optimising the surface treatment.

By mean of that, in the experimental work it was researched the influence of surface roughness on adhesive joint strength considering the joints made of two types of adherends (aluminium and stainless steel). The all bonded joints have been made using a two-component high-strength engineering adhesive. The experimental investigation doesn't prove surface roughness influence on strength characteristic of the joints in observed range of surface roughness. However, these characteristics depend strongly on adherend type involved and lap length, particularly. It is also important to note: for hard materials like stainless steel, preparing with grinding doesn't give very higher values of surface roughness parameters, unlike soften materials like aluminium where those values are achieved. Thereby, one can conclude that preparing of soften materials have more influence on final adherent roughness.

Whereas this paper is a part of extended investigation of adhesive joint, in further work, it will be investigated the influence of different surface treatment on adhesive joint strength in different atmospheric conditions.

6. LITERATURE

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