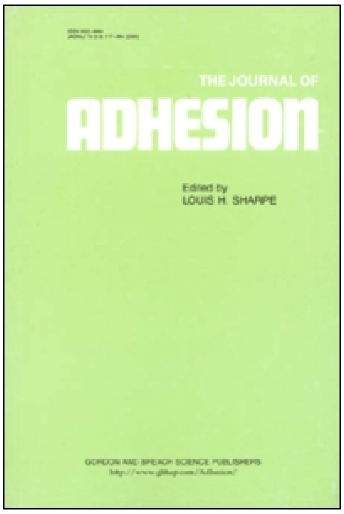


The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Influence of the Surface Finish on the Shear Strength of Structural Adhesive Joints and Application Criteria in Manufacturing Processes

J. M. Arenas Reina[a]; J. J. Narbón Prìeto[a]; C. Alía García[a]
[a] Polytechnic University of Madrid, Madrid, Spain

To cite this Article Reina, J. M. Arenas , Prìeto, J. J. Narbón and García, C. Alía(2009) 'Influence of the Surface Finish on the Shear Strength of Structural Adhesive Joints and Application Criteria in Manufacturing Processes', The Journal of Adhesion, 85: 6, 324 — 340

To link to this Article: DOI: 10.1080/00218460902880164

URL: http://dx.doi.org/10.1080/00218460902880164

The Journal of Adhesion, 85:324–340, 2009
Copyright © Taylor & Francis Group, LLC
ISSN: 0021-8464 print/1545-5823 online
DOI: 10.1080/00218460902880164

Taylor & Francis
Taylor & Francis Group

Influence of the Surface Finish on the Shear Strength of Structural Adhesive Joints and Application Criteria in Manufacturing Processes

J. M. Arenas Reina, J. J. Narbón Prìeto, and C. Alía García
Polytechnic University of Madrid, Madrid, Spain

In order to obtain the advantages of structural adhesives, a specific design of the adhesive joint is required, enhancing its performance and restricting its limitations. One of the most relevant geometrical patterns is the surface finish of the substrates as it decisively influences the mechanical properties of the joint and has a clear economical impact on the large series manufacturing processes. The contact of the adhesive with the metal (that in some cases is an activator of polymerization) and the presence of air bubbles trapped in the roughness (if abundant and larger than the polymer molecules) can lead to the appearance of cracks, causing the fracture of the adhesive layer or an adhesive failure. The objective of the present report is to analyse the influence of the roughness (as a pre-treatment before bonding) on the mechanical performance of the joint and, by means of the application of the "Value Analysis" technique, propose the surface finish that combines best both mechanical performance and suitability to the manufacturing process. The obtained results provide excellent expectations to achieve high performance of the adhesive joint with more economical and environmentally friendly surface finishes than rough machining (less waste of material, less costs in tooling and machinery, lower manufacturing times, etc.) and, therefore, enabling a better and wider use of adhesives in the industrial manufacturing processes.

Keywords: Joint design; Manufacturing processes; Structural adhesives; Surface finish

Received 14 July 2008; in final form 12 January 2009.

Presented in part at the 2nd International Conference on Advanced Computational Engineering and Experimenting (ACE-X 2008), Barcelona, Spain 14–15 July, 2008.

Address correspondence to J. M. Arenas Reina, Polytechnic University of Madrid, E. U. Ingeniería Técnica Industrial, C/ Ronda de Valencia, 3, 28012 Madrid, Spain. E-mail: josemanuel.arenas@upm.es

1. INTRODUCTION

Structural adhesives are more frequently used in manufacturing processes as they provide numerous advantages when compared with the traditional joint systems, such as welding or riveting (less weight, uniform stress distribution, etc.). However, obtaining these advantages requires a specific adhesive joint design that improves its performance and restricts its limitations [1]. The analysis of the main contributions on design rules of structural adhesive joints [2–4] together with results of studies on the selection of adhesives [5,6] and joint analysis [7,8] allows structured planning for adhesive joints design.

For this purpose, it is necessary to delve further into the knowledge and characterisation of the mechanical properties of this type of joint depending on the technical and geometrical parameters. One of the most relevant geometrical parameters is the surface finish of the substrates, as this has a decisive influence on the mechanical properties of the joint and has a clear economic impact on the mass production manufacturing processes.

The variables characteristic of the adhesive, such as viscosity and curing time, have a decisive influence on the penetration of the polymer chains of the adhesive in the substrate surface holes, which influences the mechanical interlocking effect. In this way, the contact of the adhesive with the metal (which in some cases acts as a polymerisation activator) and the presence of air bubbles inside the adhesive or entrapped between the substrate and adhesive, can lead to the formation of cracks that may break the layer of adhesive or cause an adhesion failure.

For high energy substrate materials increasing the roughness of the bonding surface causes an increase of the effective contact area. Therefore, initially, we could expect that an increase in the surface roughness of the substrates leads to an increase in the strength, regardless of the nature of the adhesive and of the adherends (mechanical theory of adhesion). However, research has confirmed that the relationship between the joint strength and the substrate roughness depends on other factors, and cannot be expressed only as a function of the substrate roughness [9]. Thus, it is considered that many of the surface treatments applied in order to generate roughness, induce physical-chemical changes that can affect the surface energy of the substrates and wettability. Surface energy, surface roughness, and adhesion were analysed by Packham [10] and the effect of surface roughness on the adhesives joints by Shahid [11].

However, most of the studies that assess the effect of roughness on the strength of adhesive joints relate the strength to the arithmetic average of the roughness (R_a) of the substrate [12–17]. Although R_a is a good estimator of the average height of the profile, this parameter does not suitably define the morphology of the surface of the substrate as it does not provide information on the height distribution (maximum and minimum), shape, and density of the peaks and valleys that make up the profile. Thus, to describe the surface roughness with greater precision it is necessary to use various statistical parameters. These are generally classified in vertical and horizontal parameters. A correct, even approximate, definition of the surface roughness requires at least three parameters (one or two horizontal parameters and one or two vertical parameters). For this reason, the present paper defines roughness of the substrate with three parameters: arithmetical average of the roughness (R_a), mean width of the profile elements (S_m), and material ratio of the profile ($R_{mr[c]}$).

To obtain different surface finishes requires the use of different manufacturing processes, each one with its own characteristics (equipment, time, tooling, etc.) and different costs. The industrial use of structural adhesive joints with a good surface preparation requires the consideration of the associated cost so that they remain competitive when compared with other joint processes such as welding or riveting. For this purpose, the present paper offers a method to assess quantitatively the cost corresponding to each process for obtaining roughness and, by means of the "value analysis" technique [18,19], proposes the surface finish that provides the best use/cost ratio.

Therefore, the objective of the present paper is to analyse the influence of the surface roughness on the mechanical performance of adhesive joints with an experimental study that characterises the surface using three statistical parameters (R_a, S_m, and $R_{mr[c]}$) and, by means of the application of the value analysis, proposes the surface finish that best combines mechanical performance and adaptability to the manufacturing process.

2. METHODOLOGY

2.1. Material, Equipment and Tooling

In order to demonstrate the procedure, one of the most used structural adhesive joint configurations was selected: a single lap joint of aluminium and acrylic adhesive, mainly used in the automobile and aeronautical sector, where light and resistant structures are required. The substrates correspond to a 6160 aluminium alloy measuring 100 × 25 × 2 mm. Figure 1 shows the single lap joint with the respective dimensions.

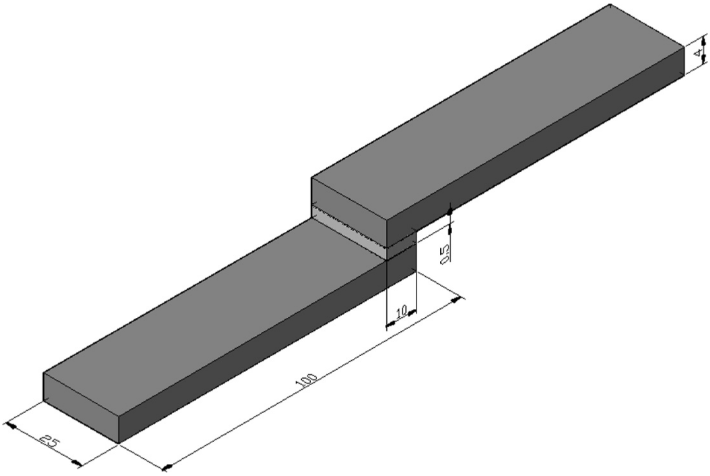
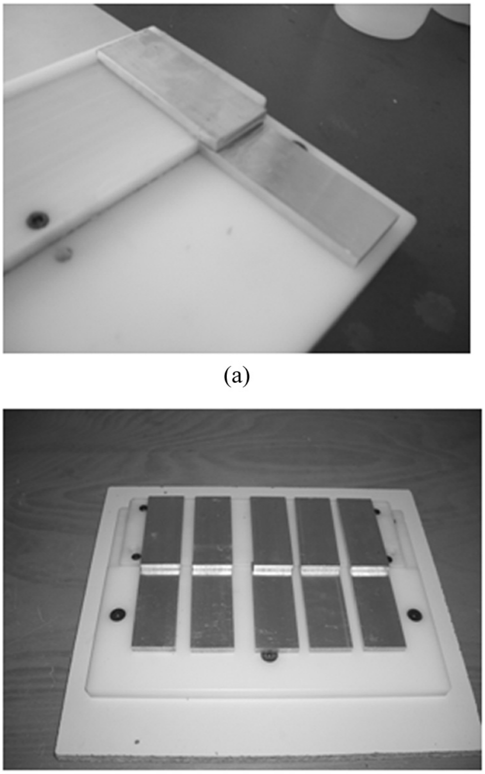


FIGURE 1 Geometrical parameters of the single lap joint (dimensions in mm).

Taking into account the material of the substrates and the shear stress to which the adhesive will be subjected, an anaerobic structural mono-component and high viscosity adhesive was chosen (Henkel Loctite® 330; Henkel, Munich, Germany). This adhesive cures between the mounted parts aided by of an activator (Loctite activator 7388; Henkel, Munich, Germany).

The surface quality of each overlap, obtained by different procedures, was defined by three statistical parameters provided by a roughness detector with a differential inductance feeler (Mitutoyo SJ-201P; Mitutoyo Corporation, Tokyo, Japan). For the cleaning and degreasing of the surface of the substrates, methyl ethyl ketone (MEK) was used. The degreasing procedure started with the cleaning of the surfaces of each substrate with absorbent paper wetted with MEK, to eliminate the dirt and grease. Then, water was applied on the treated surface with a spray. After that, a stream of hot air was applied to the surface from a drier in order to leave the surface dry and clean.

In order to ensure the necessary repetition of the experiments and maintain the geometrical parameters invariable (overlap length and adhesive thickness), a polyethylene assembly tool was designed (Fig. 2), adjustable with plastic shims that allow obtaining the desired thickness of the adhesive with great precision (precision of ±0.01 mm) and have a stable support during the resting time (2 h). Figure 2 shows the polyethylene mould used to manufacture the single lap joints.


(a)

(b)

FIGURE 2 Detail of joint assembly in the (a) mould and (b) mould used with 5 specimens.

After, in the stage of curing, it is very important to maintain the same environmental conditions (temperature and relative humidity). By means of the acclimatisation of the room, the temperature was kept stable (25 ± 0.4°C). As the relative humidity is a critical factor on the joint strength, a dry chamber was designed for the homogeneous curing of the adhesive. The chamber included silica gel (in spheres of a diameter of between 2 and 5 mm) and a filter to collect the humidity, chlorine-free and biodegradable, with a saturation indicator. The chamber also included a support perforated for the filter and a thermo-hygrometer for monitoring purposes during the curing time. Inside the chamber, the relative humidity was kept between 34 and 36% for the entire curing time (72 h).

After the curing time, the joints were removed from the chamber. A dimensional verification was carried out with a digital gauge and

FIGURE 3 Experimental set-up.

the tensile test was conducted after test. For the tensile tests, a model TN-MD machine (HOYTOM, S.L., Bilbao, Spain), motorised with automatic control *via* a computer, was used. Its capacity is 200 kN, the piston stroke length is 125 mm, and the displacement rate was fixed at 2 mm/min. Tab ends were used to improve joint alignment (Fig. 3).

2.2. Preparation of the Test Specimen Surface

In order to obtain the different degrees of surface roughness in the aluminium, the following manufacturing processes were used:

- Rough machining with an angle grinder with a rough grinding zirconium-laminated abrasive disk (granulation 60) was used to obtain roughness R_a between 5 and 6 μm, depending on the intensity of the machining.
- Sanding using granulated emery paper. Roughness R_a between 1 and 4 μm was obtained, depending on the type of grain used (between 0 and 3).
- Surface polishing with a textile disk tool attached to a small hand drill. Roughness R_a between 0.4 and 0.1 μm was obtained, depending on the number of passes.

Additionally, the original surface finish of the aluminium was considered. This original finish corresponds to a lamination process, and its roughness R_a is 0.5 μm.

Once the surface finish process was completed, the surface was cleaned with absorbent paper wetted with MEK to degrease the surface and facilitate the correct measuring of the roughness.

2.3. Manufacture of the Single Lap Joints

The repeatability of the experiments was assured with a strict control of the environmental conditions, temperature, and humidity, among others, in our laboratory:

- Laboratory: relative humidity of 44 ± 6% and temperature of 25 ± 0.4°C.
- Curing chamber: relative humidity of 35 ± 1% and temperature of 26 ± 1°C.

The polyethylene assembly tool was gauged to achieve the desired adhesive thickness (0.5 mm) after the aluminium substrates were prepared. The lower substrate, located in the assembly tool, receives the adhesive (with a manual dosifier) and the other substrate receives the activator (with spray) before being placed on the tool. Once assembled, the excess adhesive was removed (to avoid possible origins of fractures) and a 0.250 kg weight was placed on the joint for 2 h. After this time, the joints were placed in the homogeneous curing chamber for the polymerisation of the adhesive for 72 h.

2.4. Tensile Tests

The experimental study consisted of a shear tensile strength test of ten samples representative of each of the surface finishes considered (eight roughnesses between $R_a = 0.1\,\mu m$ and $R_a = 6\,\mu m$) following standard UNE-EN 1465 on the determination of the shear strength of single lap joints adhesively bonded with rigid substrates [20].

3. RESULTS AND DISCUSSION

3.1. Roughness

To obtain a wide range of roughnesses, different manufacturing processes were considered. These varied from rough machining with an angle grinder to polishing going through various emery papering with different grain sizes (from value 0 to 3). Thus, roughness values between $R_a = 0.08$ and 6.7 μm were obtained.

TABLE 1 Surface Finish (R_a, S_m, and $R_{mr[c]}$) Obtained with the Various Manufacturing Processes

	R_a (μm)				S_m (μm)				$R_{mr[c]}$(%)			
	Min.	Max.	Mean	Standard deviation	Min.	Max.	Mean	Standard deviation	Min.	Max.	Mean	Standard deviation
Polished	0.09	0.15	0.12	0.03	198	339.5	251.27	55.88	0	1.84	0.73	0.71
Lamination	0.35	0.5	0.42	0.06	99	173.17	136.43	29.07	0.17	2.5	0.87	0.93
Sanding												
Grain 0	1.01	1.08	1.04	0.03	30.34	37.67	34.43	2.93	0	1.34	0.53	0.49
Grain 1	1.98	2.04	2.01	0.02	33.67	53.67	47.1	7.73	0.67	1.34	0.9	0.28
Grain 2	3	3.08	3.03	0.03	64.5	72.67	69.17	2.94	0.5	1	0.77	0.19
Grain 3	3.88	4.03	3.97	0.05	78.34	93.5	82.9	6.19	0.67	3.17	1.47	0.98
Grinding												
Fine	4.76	5.57	5.17	0.34	108.3	136.83	118.92	13.39	1.5	2.67	2.17	0.59
Coarse	5.89	6.66	6.2	0.33	112	155	132	19.11	1.33	2.17	1.75	0.35

To define each type of surface, three roughness parameters were considered:

- R_a, which is the arithmetic mean of the absolute values of the profile deviations (Yi) from the mean line.
- S_m, which is the mean width of the profile elements. A portion projecting upward over the given upper count level is called a peak, and a portion projecting downward below the given lower count level is called a valley. The mean of the profile element (profile peak and the adjacent profile valley) widths within a sampling length is defined as S_m.
- $R_{mr[c]}$, which is the material ratio of the profile. It is the ratio (%) of the material length of the profile elements at a given level (slice level) to the evaluation length. Here the slice level is defined as the depth from the highest peak, and is called a "peak reference." The slice level is represented by a ratio of the depth (0 to 100%) to the R_t value (R_t is the total height of the profile).

Table 1 shows the maximum, minimum, and average values, and the typical deviation of each one of the parameters for each manufacturing process. It should be noted that R_a, S_m, and $R_{mr[c]}$ are independent parameters, characteristic of each manufacturing process, and therefore, necessary to unmistakably define each surface finish. This fact can be seen in the graphs R_a vs S_m, R_a vs $R_{mr[c]}$, and S_m vs $R_{mr[c]}$ that show the parameters do not have a direct relationship. For example, Fig. 4 shows the correlation graphs between the different parameters used for the emery papering process with grain 2.

3.2. Strength of the Adhesive Joints

In the tests carried out, the load/displacement curves were linear until failure and, in all the cases, failure was cohesive. Figure 5 shows the load/displacement curve and the failure surface for the emery papering process case (with grain 2) for illustrate purposes. Table 2 shows the values obtained from the average shear strength (τ: failure load/bonded area) for each manufacturing processes. Figure 6 shows a graph with the average variation of the shear strength (in MPa) as a function of the manufacturing process used. The following conclusions can be drawn from this figure:

- The surface finish obtained with the grinding (R_a larger than 4 mm) provides relatively constant strength values. These values are lower than in other manufacturing processes (except lamination process

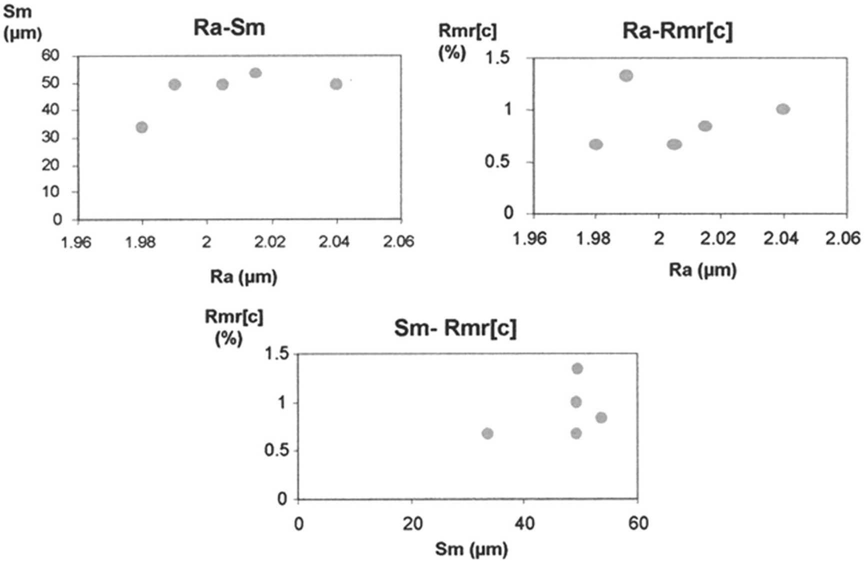
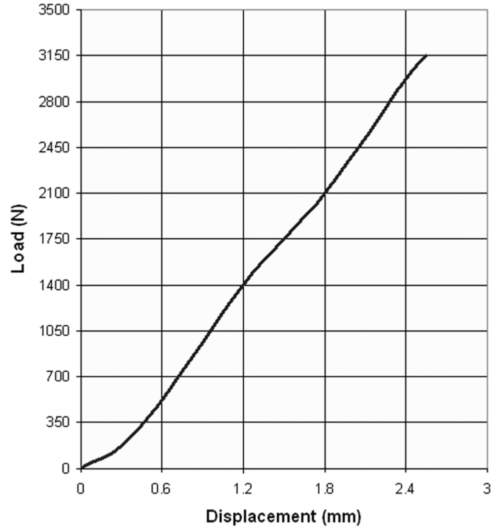


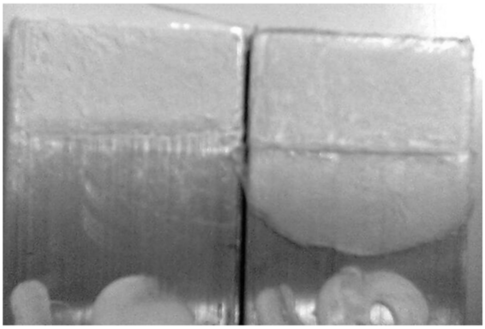
FIGURE 4 Correlation graphs between the different parameters used for the emery papering process with grain 2.

with $R_a = 0.4\,\mu m$, $S_m = 136.43\,\mu m$, and $R_{mr[c]} = 0.87\%$). These results may be explained by the fact that an inefficient wetting produces a greater number of holes (crack promoters) which cause a greater probability of failure. This effect would be compensated and equilibrated by the mechanical interlocking of surfaces with a great superficial roughness [21].

- The surface finish obtained with emery paper (R_a between 1 and 4 μm, S_m between 34 and 83 μm, and $R_{mr[c]}$ between 0.5 and 1.5%) provides a variation of the shear strength, with a maximum for $R_a = 3.03\,\mu m$, $S_m = 69.17\,\mu m$, and $R_{mr[c]} = 0.77\%$. These surface finishes provide strength values higher than those of the grinding process. These results may be explained by a possible improving in the wettability in relation to the grinding processes.
- The original surface finish or lamination (R_a between 0.35 and 0.5 μm, S_m between 99 and 173 μm, and $R_{mr[c]}$ between 0.17 and 2.5%) provides the lowest value of shear strength. The possible formation of a thin layer of aluminium oxide greatly influences adhesion in a negative way.
- The surface finish with mechanical polishing ($R_a = 0.12\,\mu m$, $S_m = 251.27\,\mu m$, and $R_{mr[c]} = 0.73\%$) provides an increase in shear strength in relation to the lamination condition. This can be



(a)



(b)

FIGURE 5 (a) Load/displacement curve and (b) failure surface for the emery papering process case (with grain 2).

explained because of possible improvement in the wettability, counteracting the loss of mechanical anchoring.

3.3. Relative Costs of the Manufacturing Processes

The analysis carried out on the surface finish of the adhesive joints is not sufficient to assess the industrial application since, in this case, it also requires the consideration of the associated costs. For this, given the different nature of the costs corresponding to each roughness

TABLE 2 Average Shear Strength Values for Each Manufacturing Process

	Roughness mean			Average shear strength τ (MPa)			
Processes	R_a	S_m	$R_{mr[c]}$	Min.	Max.	Mean	Standard deviation
Polished	0.12	251.27	0.73	7.06	8.88	7.84	0.69
Lamination	0.42	136.43	0.87	4.48	5.39	4.87	0.39
Sanding							
Grain 0	1.04	34.43	0.53	8.52	10.47	9.62	0.83
Grain 1	2.01	47.10	0.90	10.32	11.48	10.82	0.52
Grain 2	3.03	69.17	0.77	9.65	11.76	11.11	0.87
Grain 3	3.97	82.9	1.47	6.49	8.59	7.52	0.79
Grinding							
Fine	5.17	118.92	2.17	7.45	6.76	7.16	0.30
Coarse	6.20	132	1.75	6.57	6.92	6.75	0.15

process, the value analysis [18,19] technique was used to select the surface finish that provides the best use/cost ratio.

The direct manufacturing costs of a certain product correspond to the labour costs (directly performing the operations), the material making up the product, and the costs of the machinery and equipment used in the manufacturing of the product. Applying these criteria to the manufacturing processes of the different surfaces, we can distinguish

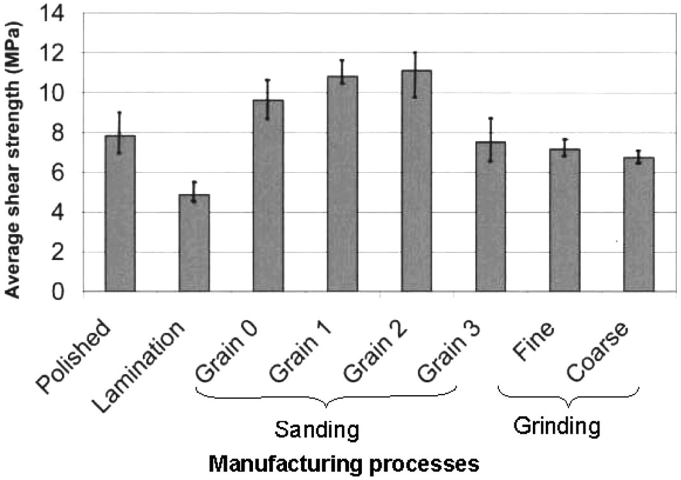


FIGURE 6 Average shear strength as a function of the manufacturing process used.

the following representative factors of the costs for obtaining each roughness:

- *Manufacturing time*. Representative of the labour costs. The longer the operator takes to manufacture a determined surface the higher the corresponding labour costs.
- *Material scrapped*. Although the starting point material is the same in all the cases, the different manufacturing processes scrap different amounts of material in order to obtain the desired surface. Thus, the lower amount of material scrapped the higher the economic performance of the process (less costs in scrapped material).
- *Tools*. Each manufacturing process analysed requires a series of tools and specific tooling. The main costs inherent to this equipment are made up by the amortisation costs, investment interest rate, maintenance, and energy consumption. The more sophisticated the equipment used for obtaining the surface, the higher the associated costs.

Tables 3, 4, and 5 show the comparative analysis of the different cost factors (time used, material scrapped, and tools) for the different manufacturing processes considered. The comparative study allows obtaining quantitative results if we consider value "0" when the factor considered has a lower cost in a process than in another process (low cost), value "1" when the factor has a higher cost than another process (high cost), and value "1/2" when they have the same cost (medium cost).

TABLE 3 Comparative Analysis of the Time Used to Obtain Each Surface Roughness

			Sanding				Grinding			
	Polished	Lamination	Grain 0	Grain 1	Grain 2	Grain 3	Fine	Coarse	Total	Weight
Polished	–	0	1/2	0	0	0	0	0	0.5	0.018
Lamination	1	–	1/2	1/2	1/2	1/2	0	0	3	0.107
Sanding										
Grain 0	1/2	1/2	–	0	0	0	0	0	1	0.035
Grain 1	1	1/2	1	–	0	0	0	0	2.5	0.089
Grain 2	1	1/2	1	1	–	0	0	0	3.5	0.125
Grain 3	1	1/2	1	1	1	–	0	0	4.5	0.161
Grinding										
Fine	1	1	1	1	1	1	–	0	6	0.214
Coarse	1	1	1	1	1	1	1	–	7	0.25
Total									28	1

TABLE 4 Comparative Analysis of the Material Scrapped in Obtaining Each Surface Roughness

			Sanding				Grinding			
	Polished	Lamination	Grain 0	Grain 1	Grain 2	Grain 3	Fine	Coarse	Total	Weight
Polished	–	1/2	0	0	0	0	0	0	1/2	0.018
Lamination	1/2	–	0	0	0	0	0	0	0	0.018
Sanding										
Grain 0	1	1	–	0	0	0	0	0	2	0.071
Grain 1	1	1	1	–	0	0	0	0	3	0.107
Grain 2	1	1	1	1	–	0	0	0	4	0.142
Grain 3	1	1	1	1	1	–	0	0	5	0.179
Grinding										
Fine	1	1	1	1	1	1	–	0	6	0.214
Coarse	1	1	1	1	1	1	1	–	7	0.25
Total									28	1

As the influence of each cost-factor (time used, eliminated material, and tools) is different in the total cost of surface-manufacturing, it is necessary to calculate this total cost using a weighted or compensated value of each factor which relates and shows this relative influence.

Taking into account that the surface processes are conventional (manual with the use of tools and machines), the most significant cost is the labour cost (time used factor) and the costs of the tools and

TABLE 5 Comparative Analysis of the Tool Costs in Obtaining Each Surface Roughness

			Sanding				Grinding			
	Polished	Lamination	Grain 0	Grain 1	Grain 2	Grain 3	Fine	Coarse	Total	Weight
Polished	–	1	1/2	1/2	1/2	1/2	0	0	3	0.107
Lamination	0	–	0	0	0	0	0	0	0	0
Sanding										
Grain 0	1/2	1	–	1/2	1/2	1/2	0	0	3	0.107
Grain 1	1/2	1	1/2	–	1/2	1/2	0	0	3	0.107
Grain 2	1/2	1	1/2	1/2	–	1/2	0	0	3	0.107
Grain 3	1/2	1	1/2	1/2	1/2	–	0	0	3	0.107
Grinding										
Fine	1	1	1	1	1	1	–	1/2	6.5	0.232
Coarse	1	1	1	1	1	1	1/2	–	6.5	0.232
Total									28	1

TABLE 6 Costs Analysis and Weighting of Each Manufacturing Process are Obtained Each Surface Roughness

	Factors and weights			
	Used time 50%	Elimination material 20%	Tools 30%	Relative costs % (≈)
Polished	0.009	0.0036	0.0321	4
Lamination	0.0535	0.0036	0	6
Sanding				
Grain 0	0.0107	0.0142	0.0321	6
Grain 1	0.0445	0.0214	0.0321	10
Grain 2	0.0625	0.0284	0.0321	12
Grain 3	0.0805	0.0358	0.0321	15
Grinding				
Fine	0.107	0.0428	0.0696	22
Coarse	0.125	0.05	0.0696	25
Total				100

tooling. Thus, the following weight was given to the cost factors: 50% to the time used, 30% to the tools and tooling, and 20% to the material scrapped. Table 6 includes the cost analysis and the weighting corresponding to each manufacturing process.

The selection of the best alternative for the manufacturing of the surfaces of an adhesive joint should consider both the technical performance of the joint (in this case average shear strength) and the costs associated with the manufacturing process. A method to optimise this selection is the use of the "value" function, defined for each

TABLE 7 Relative Strength, Relative Costs, and "Value" of Each Manufacturing Process

	Costs weighted	Relative costs %	Average shear strength (τ) MPa	Relative strength %	Value
Polished	4	16	7.84	70.5	4.31
Lamination	6	24	4.87	43.9	1.83
Sanding					
Grain 0	6	24	9.62	86.6	3.61
Grain 1	10	40	10.82	97.4	2.43
Grain 2	12	48	11.11	100	2.10
Grain 3	15	60	7.52	67.7	1.13
Grinding					
Fine	22	88	7.16	64.4	0.73
Coarse	25	100	6.75	60.8	0.61

manufacturing process as the ratio between the "relative use" (relative strength) and the "relative cost". Table 7 shows relative strength, relative cost, and value for each manufacturing process. It can be seen than the value is maximum for the polished process.

4. CONCLUSIONS

Although the highest strength is obtained with surface finishes obtained by rough machining ($R_a = 3\,\mu m$, $S_m = 69.17\,\mu m$, and $R_{mr[c]} = 0.77\%$), the application of the value analysis which optimises the use/cost, provides very satisfactory values for soft machining by polishing with $R_a = 0.12\,\mu m$, $S_m = 251.27\,\mu m$, and $R_{mr[c]} = 0.73\%$. This result provides excellent expectations to achieve high performance of the adhesive joint with more economical and environmentally friendly surface finishes than rough machining (less waste of material, less costs in tooling and machinery, lower manufacturing times, etc.) and, therefore, enables a better and wider use of the adhesives in industrial manufacturing processes.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Mario Madrid from Henkel for providing the adhesive used in this work. At the same time, the authors would like to acknowledge the Autonomous Community of Madrid and Polytechnic University of Madrid for financing the present project.

REFERENCES

[1] LeBack, C., Brechet, Y., Shercliff, H. R., Jeggy, T., and Salvo, L., *Materials and Design* **23**, 405–416 (2002).

[2] Adams, R. D., Comyn, J., and Wake, W. C., *Structural Adhesive Joints in Engineering*, (Chapman & Hall, London, 1997).

[3] Van Straalen, I. J. J., Wardenier, J., Vogelesang, L. B., and Soetens, F., *Int. J. Adhes. Adhes.* **18**, 41–49 (1998).

[4] Reis e Silva Grundmüller, P., *Worldwide Design Handbook*, (Loctite European Group, Munich, 1998).

[5] Edwards, K. L., *Materials and Design* **19**, 121–123 (1998).

[6] Suarez, J. C., Diez de Ulzurrún, I., Biezma, M. V., Ruiz Román, J. M., Martinez, M. A., Del Real, J. C., and López, F., *J. Mater. Process. Tech.* **143–144**, 219–224 (2003).

[7] Arenas, J. M., González, C., Guillamón, A., and Sebastián, M., *Ing. Quim.* **396**, 93–102 (2002).

[8] Arenas, J. M. and Guillamón, A., *Int. J. Adhes. Adhes.* **27**, 122–128 (2007).

[9] Packham, D. E., *1st Internat. Congress on Adhesion Science and Technology* **81–108** (1998).

[10] Packham, D. E., *Int. J. Adhes. Adhes.* **23**, 437–448 (2003).

[11] Shahid, M. and Hashim, S. A., *Int. J. Adhes. Adhes.* **22**, 235–244 (2002).

[12] Katona, T. R. and Batterman, S. C., *Int. J. Adhes. Adhes.* **3**, 85–91 (1983).

[13] Sekercíoglu, T., Rende, H., Gülsöz, A., and Meran, C., *Int. J. Adhes. Adhes.* **142**, 82–86 (2003).

[14] Lunder, O., Lapique, F., Johsen, B., and Nisancioglu, K., *Int. J. Adhes. Adhes.* **24**, 107–117 (2004).

[15] Prolongo, S. G., Yuste, V., Del Rosario, G., and Ureña, A., *VI Jorn. Adhes.* (2005).

[16] Diao, D. and Kandori, A., *Tribology International* **39**, 849–855 (2006).

[17] Ozdemir, T. and Hiziroglu, S., *J. Mater. Process. Tech.* **186**, 311–314 (2007).

[18] Kalpakjian, S. and Schmid, S. R., *Manufacture Engineering and Technology*, (Pearson-Prentice Hill, Upper Saddle River, NJ, 2006), pp. 1266–1269.

[19] Arenas, J. M., *Calidad e Ingeniería de Diseño*, (Fundación General UPM, Madrid, 2001), pp. 145–152.

[20] UNE-EN 1465, *Adhesivos: Determinación de la Resistencia a Cizalladura por Tracción de Juntas Pegadas de Sustratos Rígidos*. AENOR (1996).

[21] Uehara, K. and Sakurai, M., *Mater. Process. Tech.* **127**, 178–181 (2002).