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Multi-criteria selection of structural adhesives to bond ABS parts obtained by rapid prototyping

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ABSTRACT

One of the most used methods in rapid prototyping is Fused Deposition Modeling (FDM), which provides components with a reasonable strength in plastic materials such as ABS and has a low environmental impact. However, the FDM process exhibits low levels of surface finishing, difficulty in getting complex and/or small geometries and low consistency in "slim" elements of the parts. Furthermore, "cantilever" elements need large material structures to be supported. The solution of these deficiencies requires a comprehensive review of the three-dimensional part design to enhance advantages and performances of FDM and reduce their constraints. As a key feature of this redesign a novel method of construction by assembling parts with structural adhesive joints is proposed. These adhesive joints should be designed specifically to fit the plastic substrate and the FDM manufacturing technology. To achieve this, the most suitable structural adhesive selection is firstly required. Therefore, the present work analyzes five different families of adhesives (cyanoacrylate, polyurethane, epoxy, acrylic and silicone), and, by means of the application of technical multi-criteria decision analysis based on the analytic hierarchy process (AHP), to select the structural adhesive that better conjugates mechanical benefits and adaptation to the FDM manufacturing process.

1. Introduction

The technological advances occurred in the recent years have facilitated the development of advanced systems for rapid prototyping. These techniques give physical models in a relatively short period (less than 24 h) from three-dimensional designs developed in a CAD system [1–3].

One of the most widely used techniques is the FDM since it provides ABS components with a reasonable strength and a very low environmental impact. FDM machines are clean, require little maintenance and use relatively inexpensive, odorless and non-toxic materials [4]. However, the FDM process has limitations in the surface finishing, which depends on the orientation between the *XY* plane and the surface. It is also difficult to set up complex or small geometries, and "slim" elements have low consistency. Finally, parts require large structures to support "cantilever" elements. All these restrictions reduce product quality and cause a significant increase in manufacturing times, costs and post-processing requirements, which limits both the range of obtainable parts (only single parts without complex interior cavity are allowed) and its scope.

Therefore, in the recent years several research works have been published (e.g., [5–8]) for improving specific attributes of parts obtained by FDM such as surface finishing or dimensional accuracy. These works modify characteristic parameters of the process, such as the thickness of each layer, orientation of the piece or structure of filling material. However, proposed modifications only have given partial improvements and have not considered an overall prototype redesign to obtain the best fit to the manufacturing process.

The solution to the deficiencies mentioned above requires a comprehensive review of part 3D-design. This allows a prototype generation enhancing FDM performances such as low environmental impact or moderate cost, and reducing limitations in macro and micro geometry. Thus, parts made by FDM will combine precision, mechanical performances and low costs, being the best alternative in comparison to other rapid prototyping processes.

As a key feature of this overall redesign a novel method of construction by assembling parts using structural adhesive joints is proposed. Joints are specifically designed to fit the plastic substrate ABS and FDM technology for manufacturing (construction using layers, dependence on construction direction, etc.). The use of adhesive joints will ease the parts redesign and will achieve the desired geometric quality with manufacturing time and cost reduction and without any loss of mechanical properties.

Adhesive bonds are used with increasing frequency in many industrial sectors, replacing or complementing traditional joining

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methods such as welding or riveting. Among the benefits of structural adhesives, should be noted their high resistance, their low weight, tightness and resistance to the galvanic corrosion [9]. Therefore, adhesives are increasingly used in many manufacturing processes in various industrial sectors (aerospace, automotive, food industry, etc.). However, to obtain the inherent advantages of adhesives, their application need a specific design of the adhesive joint that enhances their performances and cut their limitations such as delicate surface preparation or reduced resistance to peel loading [10–12].

Therefore, many research papers have been made to set up analytical models of structural adhesive joints to better understand the adhesive behavior and to propose criteria for optimizing the joints design [13,14]. When the geometry of the joint is complex, many researchers have used the finite element method for simulating the behavior of the adhesive joint (e.g., [15–18]).

The integration of these works together with major contributions on design rules of structural adhesive joints [19], studies on the selection of adhesives [20,21] and geometric analysis of joints [22], allows developing a structured plan for the design of structural adhesive joints [23]. When it requires an analysis of the adequacy of structural adhesive joints in industrial production, these studies are complemented by technical and economic considerations, which assess the overall adequacy process [24,25].

This work, keeping in line with this holistic approach to adhesive joint design, in the first phase deals with the analysis and selection of the adhesive, which best combines mechanical performances and suitability to the manufacturing process FDM (dimensional quality, safety and cost of the procedure preparation). Therefore, adhesives of five different families have been analyzed: cyanoacrylate, epoxy, polyurethane, silicone and acrylic. The integration of quantitative experimental findings and the quality assessment for the process suitability in a multi-criteria decision analysis (MCDA), allows selecting the best alternative.

MCDA is a broad term that comprises many methods and techniques that are intended to assist in making complex decisions involving many aspects or attributes. The main aim is to optimize the decision as a compromise between a set of attributes, usually in conflict [26]. In this work, the technique used is based on the method of analytic hierarchy process (AHP). This technique is suitable when the number of alternatives is discrete and is based on the establishment of a hierarchical structure of the problem that supports the integration of conflicting criteria [27].

2. Methodology

2.1. Material, equipment and tools

Selection of adhesives used in the trials, has taken into account the suitability for joining ABS substrates. Moreover, they should be representative enough of one of each main families of structural adhesives. Thus, the following adhesives have been chosen:

- Acrylics: SikaFast® 5211adhesive by SIKA.
- Polyurethane: Two component adhesive SikaForce® 7710 SikaForce® ll00 and 7010 by SIKA.
- Cyanoacrylate: Loctite® 420 by Henkel.
- Epoxy: A two component adhesive Loctite® 9489 by Henkel.
- Silicone: Loctite® 5910 by Henkel.

Table 1 shows the main features of previous adhesives.

Substrates used are prismatic parts of ABS (Acrylonitrile–Butadiene–Styrene) of 50 × 7 × 7 mm obtained by FDM. The FDM machine is a Dimension BST 768 with Catalyst software and work area of 203 × 203 × 305 mm. The substrates have been built by adding ABS layers 0.2 mm thick (parallel to the *XY* plane) with rectangular shape 50 × 7 mm, up to a height of 7 mm. In these conditions, the most relevant features of the substrates are the tensile strength (20.3 MPa in coaxial direction to the construction axis *X*), the elasticity modulus (1.4 MPa) and the surface roughness (Ra = 2.7 μm)

Due to the anisotropy of the substrate (which has a better performance to resist efforts in parallel directions into the construction plane *XY*) the butt joint model has been chosen to perform tensile tests with the adhesives. Fig. 1 shows the dimensions of the butt.

One of the most delicate aspects in the realization of an adhesive bond is the preparation of the substrate surface. Firstly, the surface of the joint is carefully sanded with sandpaper (grain size P600) obtaining a roughness Ra of 2.1 μm or less. Then the substrate is cleaned with absorbent paper and hot air is applied to remove any particles attached.

An expanded polystyrene (PS) tooling has been designed and constructed in order to ensure the necessary repeatability of experiments and to keep geometric parameters invariant (thickness of adhesive and proper alignment of substrates). This tooling also serves as a support during the standing time. Fig. 2 shows the tooling used to produce the butt joints.

After the standing time the curing phase starts. At this stage it is very important to maintain the same environmental conditions (temperature and relative humidity). By cooling the room temperature has remained stable (25 ± 0.4 °C). As the relative humidity is a

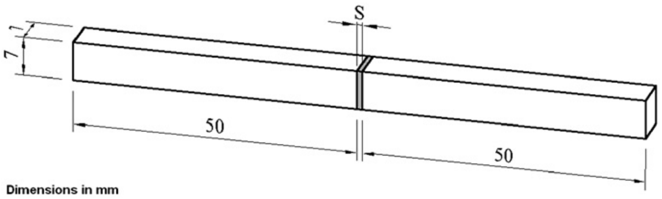

Fig. 1. Dimensions of the butt joint (mm).

Table 1
Main features of selected adhesives.

Adhesive	PROPERTIES				
	Shear Strength ISO 527 (MPa)	**Viscosity (mPa s)**	**Rest time (min)**	**Curing time (min)**	**Safety and health**
Acrylic SikaFast® 5211 (bicomponent)	9	–	0.5	3	Irritant
Polyurethane SikaForce® 7710 L100 + 7010 (bicomponent)	9	10000	100	230	Mildly irritant
Cyanoacrylate Loctite® 420 (monocomponent)	15	1–5	0.1	0.25	Irritant
Epoxy Loctite® 9489 (bicomponent)	14	60,000	300	7 days	Irritant and corrosive
Silicone Loctite® 5910 (monocomponent)	1.7	–	40	20 days	Harmful