AQ1 AQ2 AQ3

Additive Manufacturing and Performance of Functional Hydraulic Pump Impellers in Fused Deposition Modeling Technology

AQ4

S. Fernández
Department of Mechanical Engineering,
Technical School of Engineering-ICAI,
Comillas University,
Madrid ■, Spain

M. Jiménez
Department of Mechanical Engineering,
Technical School of Engineering-ICAI,
Comillas University,
Madrid ■, Spain

J. Porras
Department of Mechanical Engineering,
Technical School of Engineering-ICAI,
Comillas University,
Madrid ■, Spain

L. Romero
Department of Construction and
Manufacturing Engineering,
School of Industrial Engineering,
Universidad Nacional de Educación a Distancia,
Madrid ■, Spain

M. M. Espinosa
Department of Construction and
Manufacturing Engineering,
School of Industrial Engineering,
Universidad Nacional de Educación a Distancia,
Madrid ■, Spain

M. Domínguez
Department of Construction and
Manufacturing Engineering,
School of Industrial Engineering,
Universidad Nacional de Educación a Distancia,
Madrid ■, Spain

Would it be possible for an additively manufactured impeller of fused deposition modeling (FDM) technology to have a functional behavior and a similar performance to that of the original impeller of a close-coupled centrifugal pump? In this research paper, different tests are conducted to answer this question and to evaluate the manufacturing process of FDM functional parts. Three performance experiments with the same centrifugal pump, using an open test rig, are carried out and compared, first using the original impeller provided by the manufacturer of the pump, second using an FDM replication of the original one without post-treatment, and third using a chemically dimethyl ketone post-treated FDM replication. The results obtained in the tests demonstrate the functional behavior of both additive FDM impellers in comparison with the one fabricated by means of conventional technology (subtractive manufacturing). Additionally, analogous head-flow curves (and also with an improved performance to the one of the original impeller) are obtained. This research paper introduces significant information concerning a low-cost and low-time manufacturing process of additive functional parts. Moreover, new results are presented regarding the performance of chemically post-treated FDM parts working in functional applications. FDM impellers of high complexity and quality, which meet performance criteria, can be achieved. [DOI: 10.1115/1.4032089] AQ5

Keywords: additive manufacturing, fused deposition modeling, FDM, equipment production, hydraulic pump, impeller performance

1 Introduction

FDM is a layer-by-layer additive manufacturing (AM) technology that enables fabrication of physical objects directly from CAD data using a heated thermoplastic filament extruded through a nozzle for building parts by incremental material deposition [1–3]. In contrast to classical methods of manufacturing, these processes are based on the additive principle for the fabrication of parts, whose main advantages are no limitation with regard to complex geometries and building time reduction depending on the geometrical complexity of the model, the requirements of the conventional process and the size of the production batch. At the present time, FDM is used not only for concept models and prototypes but also for final functional parts [3,4]. AQ6

There is a previous research about the manufacturing and performance of the FDM impellers of pumps. FDM is used with a time-cost reduction approach in order to redesign the blades of a turbine [5]. A mixed impeller is tested, with FDM blades and a metallic body. FDM is evaluated in order to decide if is optimal for fabricating a prototyping model of a pump impeller [6]. The mean roughness (Ra) of the FDM model is 12.5 μm and, therefore, the authors indicate the requirement to polish and coat the model with some material to seal its porous surfaces. Consequently, and due to the outstanding disadvantage of this model, the FDM technology is discarded in the study. And finally, the results in Ref. [7] have shown that FDM is a viable and feasible method of producing impellers to be tested and to help the pump designer to test low-cost prototypes of new and complex blade geometries.

So as to make a contribution beyond other previously published investigations, in this research paper:

- Entire FDM impellers and not only FDM blades will be studied.
- The performance tests will be extended beyond prototypes for preliminary testing.
- The roughness of FDM impellers without post-treatment will be analyzed as a potential problem or limitation regarding its proper performance.
- The performance of chemically post-treated FDM impellers operating in functional applications will be investigated.

The main purpose of this investigation aims to obtain impellers with a hydraulic capacity and high performance using FDM and a subsequent finishing external chemical process.

In this study, the performance of three centrifugal pump impellers will be tested and compared: the original one provided with the centrifugal pump and two additively manufactured replications of the original, one untreated and one post-treated, in order to evaluate the effect of a chemical external agent on the strength of the impeller. The post-treatment process is based on the immersion of the impeller in a dimethyl ketone water solution which dissolves the material externally and improves the surface quality of the part [8].

Contributed by the Design for Manufacturing Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received February 15, 2015; final manuscript received November 12, 2015; published online xx xx, xxxx. Assoc. Editor: Shapour Azarm.

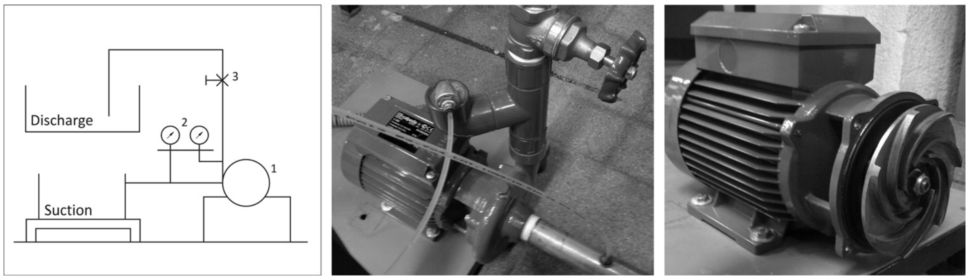

Fig. 1 Test rig: pump (1), pressure gages (2), and valve (3)

2 Materials and Methods

2.1 The Studied Application. The performance of the impellers is experimentally investigated in an open test rig (Fig. 1) used to measure the flow rate with seven complete test cycles per impeller, according to ISO 9906 standard—hydraulic performance acceptance tests for rotodynamic pumps. The water level of the suction tank is maintained constant by another external pump.

The tested application is a close-coupled horizontal and centrifugal pump with a semi-open impeller. The model reference of the pump "Calpeda C 20 E B-C20/A" is driven by a three-phase AC electric motor.

2.2 The Impeller CAD Model. The process begins with the conversion of the impeller CAD model into the impeller STL model using SOLID EDGE ST6 software (conversion tolerance of 0.01 mm and surface plane angle of 0.5 deg) (Fig. 2).

2.3 Decision of the AM Technology. The main AM categories according to ISO 17296-2:2015 are: vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition, and sheet lamination. The AM technology of a part should be properly chosen depending on the main aim that is supposed to be achieved: aesthetic, functional, experimental, or visual [9]. The FDM technology (material extrusion category) is selected to produce the impellers owing to its tensile, bending and impact strengths, its heat stability, and its chemical resistance to achieve functional parts [5] (Fig. 2). Moreover, a plastic-based AM technology is chosen over a metal-based AM technology considering that pumped liquids with acid inclusions are the main cause of corrosion failure of metal impellers [10]. Plastic impellers made of acrylonitrile butadiene styrene (ABS), polyethylene or PVC are used in most installations and have the advantages of being lightweight and corrosion-resistant [11,12]. In addition to this, the FDM technology is also selected due to its cost given that two economical materials associated to FDM can be employed, ABS and polylactic acid (PLA). ABS is finally selected for the reason that in comparison to PLA, ABS has a longer lifespan and a higher strength. PLA is more brittle than ABS and will tend to splinter and break [13].

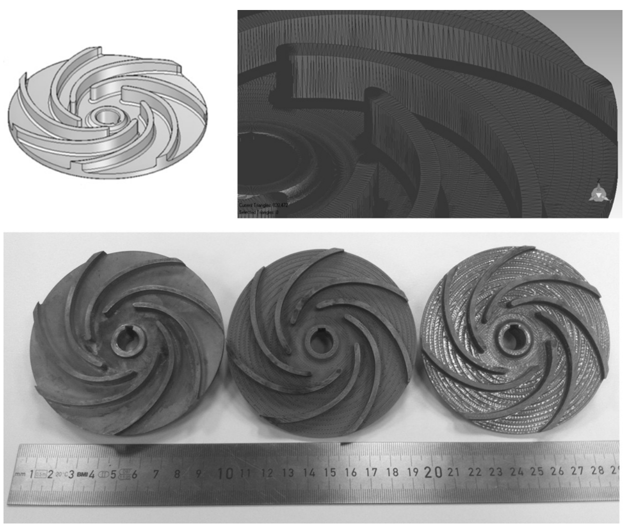

Fig. 2 CAD and STL models, original impeller (Brass P-Cu Zn 40 Pb 2 UNI 5705), untreated and post-treated FDM impellers (mm scale). Stratasys Dimension SST 768. Build platform, *X-Y-Z* axes definition and built orientation of the impellers.

2.4 The FDM Impellers. The FDM impellers have been fabricated by depositing incremental layers in the *XY* plane. As far as FDM technology is concerned, the orientation of the impeller on the working tray of the machine is a crucial variable of the process. The impellers are built in the *Z* orientation on the *XY* layers as the obtained surface roughness of the flow direction surfaces is of a higher quality than one of the impellers built in the *X* and *Y* orientations. Additionally, in this *Z* orientation the profile of the blades is the optimal one because the geometry of its contour is fabricated in the *XY* plane.

To this aim, the "Stratasys Dimension SST 768" commercial machine and the Catalyst 4.4 application for interfacing have been employed. In this research, the parameters of the process are: a 0.254 mm layer resolution since it is the most accurate that the machine is able to perform; a solid model interior given that it is the appropriate one for functional parts; and a smart support fill due to it being optimized from the point of view of material used and being the one that interacts less with the fabricated part. Therefore, a postprocess removal is avoided and the results of the research are protected from being affected by this removal. And the parameters preset by the machine manufacturer are: a chamber temperature of about 74 °C and an extrusion nozzle temperature of about 102 °C.

The material, time, and cost comparison between impellers can be summarized as follows:

- FDM impeller without treatment: 28.6 g mass, 30.94 cm^3 model material, 18.30 cm^3 support material, 3 hrs manufacturing time, and 40€manufacturing cost.
- FDM impeller with treatment: 28.4 g mass, 30.94 cm^3 model material, 18.30 cm^3 support material, 3 hrs manufacturing time, and 40€manufacturing cost.
- Conventional machined metal impeller (unitary production): 251.6 g mass, 2d manufacturing time, and 150€ manufacturing cost.

The FDM cost includes the materials (model, support, and tray), the machine (price, amortization, and maintenance), and the manpower costs of the preparation, manufacturing and post-treatment processes, and this cost has been calculated according to the recommendations in Refs. [14–16]. The difference between the mass of the original and the FDM impellers only influences the overall efficiency of the pump in terms of the mechanical efficiency (rotating mechanical masses and mechanical losses, with

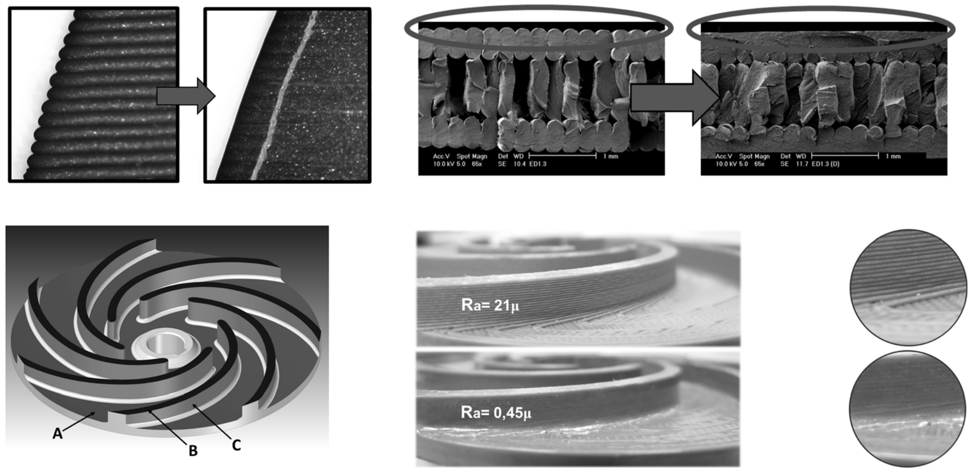

Fig. 3 Effect of the dipping bath in the FDM test specimens of previous investigations of the authors obtained using a scanning electron microscope. Rear shroud (*A*) and open blades (*B* top, *C* side) of the impeller. Ra of the side of the open blade.

no consideration given to hydraulic effects). Hence, this difference is not expected to affect the performance results of the test, given that once the operating steady-state is reached, the mass of the impeller does not influence the head-flow curve of the pump [17–19].

2.5 Post-Treatment of the FDM Impeller. The surface roughness controls the magnitude of the hydraulic and friction losses in the impeller of a pump [20–22]. The first impeller studied is an untreated one and its mean roughness will be analyzed as a potential limitation regarding the proper performance of the pump. The second impeller studied is a post-treated one so as to improve its surface quality and test an FDM impeller with a similar roughness to the one of the original impeller of the pump, and concurrently to analyze the effect of an external and chemical agent on an FDM functional part and to evaluate its mechanical behavior taking into consideration the results presented in previous research papers of post-treated FDM test specimens in comparison with raw ABS test specimens [23–25]. The chemical post-treatment process involves a 20-s dipping bath of the impeller using acetone $(CH_3)_2CO$ (dimethyl ketone) which melts the top layers, enhancing the surface finish of the FDM part (Fig. 3). The organic solvent containing strong polar groups overrules polymer–polymer interactions in order to consolidate the polymer segments of a plastic that exhibits strongly polarizable side groups.

3 Analysis and Results

The arithmetic average of the absolute values of the roughness profile ordinates, the mean roughness (Ra), for the rear shroud and for the open blades of the three impellers used in this research is measured using the Zeiss SURFCOM 1500 roughness tester (Fig. 3).

The results of the surface measurement can be summarized as follows:

- Original impeller pump: (A) Ra = 0.67 μm, (B) Ra = 1.6 μm, (C) Ra = 1.5 μm.
- FDM impeller without treatment: (A) Ra = 19.9 μm, (B) Ra = 13.9 μm, (C) Ra = 21 μm.
- FDM impeller with treatment: (A) Ra = 1.1 μm, (B) Ra = 0.7 μm, (C) Ra = 0.45 μm.

Afterward, the three head-flow curves of the pump are obtained (Fig. 4) from the results of the test cycles of the impellers. An average downward deviation of 0.2% from the reference curve of the original is observed in the heads of the untreated FDM impeller curve. On the contrary, an average upward deviation of 2.1% from the reference curve of the original is observed in the heads of the treated FDM impeller curve. These deviations are clearly noticeable in the high flow operating range of the curve.

On the one hand, the inherent porosity of the untreated FDM impeller adversely affects the performance of the pump owing to liquid losses in the inner geometry of the impeller. On the other hand, an increase in the volumetric efficiency of the pump using the treated FDM impeller is observed. In other words, the liquid losses in the pump during the compression process have decreased due to the effect of the solvent in the outer geometry of the impeller, seeing as the geometry of the impeller slightly widens and the inner clearances are reduced.

Moreover, both phenomena and their relationship with the original impeller curve are directly connected to the difference between the mean roughness of the original impeller and the FDM impellers, an improved one in the case of the treated and a worsened one in the case of the untreated. In order to obtain optimum performance in a centrifugal pump, the water passages should be as smooth as possible. Despite the fact that the degree of surface

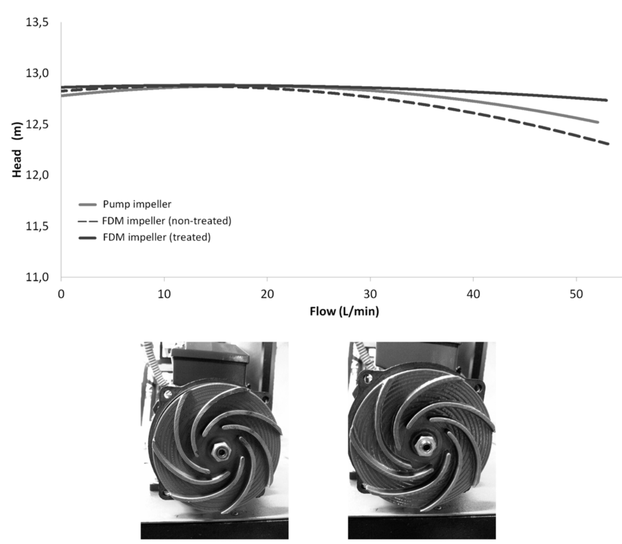

Fig. 4 Head-Flow curves of the three tested impellers. The impeller mounted on the pump after the tests with (*a*) and without (*b*) chemical post-treatment.

finish has no effect on the general shape of the head curves, the performance is higher in the case of the smooth impeller and likewise more stable in the high flow operating range. The roughness of the impeller surfaces decreases the pump performance [21].

The height, pitch, and density of the elements of roughness as well as their direction with respect to the flow have an important impact on the losses [22]. An enhancement in the surface quality of an impeller achieves a 2–3% improvement of the performance of the pump [26] and the results in the study of this research paper are exactly within this range.

At the end of this experiment, none of the FDM impellers have suffered any damage or degradation (Fig. 4). The useful life of plastic impellers is expected to be at least equal to the one of metal impellers given the fact that ABS has proper mechanical properties and if the pumped liquid is chemically neutral to the plastic of the impeller [27].

4 Conclusions and Future Work

In conclusion, in this study, AM and FDM have been demonstrated to be low-cost and low-time processes used to manufacture impellers that render the performance of the original ones in standardized head-flow curve tests. The FDM impellers were fabricated in a noticeably reduced time in comparison with that of the conventional manufacturing technology, with a material and finishing treatment that meet the mechanical and hydraulic requirements, and at a competitive cost. These functional impellers could be used in the approval processes for updating and redesigning new impeller models to meet the requirements for pump performance according to international regulations.

The main contributions and findings of this research paper are:

- That an impeller fabricated using AM FDM technology (an entire FDM impeller and not only FDM blades) has a functional behavior and a similar performance to the original impeller of the rotodynamic hydraulic pump.
- That the inherent roughness in the FDM manufacturing process of the external surfaces of the impeller is not a limitation in the results of the head-flow curve of the pump.
- That the improvement of the surface quality of the FDM impeller using a low-cost chemical post-treatment provides an enhancement in the performance of the pump and a greater stable behavior in the high flow operating range of the pump.

Further developments are being conducted by the authors in addition to this study, so as to achieve advanced and significant results and conclusions with regard to FDM additive impellers and their performance. The study that is described in this research paper is being repeated with impellers of different materials, with semi-open impellers of different geometries and with closed impellers, making use of test rigs that consist of not only an FDM impeller but also an FDM pump body.

References

[1] Crump, S. S., 1992, "Apparatus and Method for Creating Three-Dimensional Objects," U.S. Patent No. 5,121,329.

[2] Crump, S. S., 1994, "Modeling Apparatus for Three-Dimensional Objects," U.S. Patent No. 5,340,433.

[3] Yongnian, Y., Shengjie, L., Zhang, R., Feng, L., Rendong, W., Qingping, L., and Zhou, X., 2009, "Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications, and Development Trends," Tsinghua Sci. Technol., **14**(S1), pp. 1–12. AQ7

[4] Ilardo, R., and Williams, C. B., 2013, "Design and Manufacture of a Formula SAE Intake System Using Fused Deposition Modeling and Fiber-Reinforced Composite Materials," Rapid Prototyping J., **16**(6), pp. 174–179.

[5] Thakker, A., Sheahan, C., Frawley, P., and Khaleeq, H. B., 2002, "Innovative Manufacture of Impulse Turbine Blades for Wave Energy Power Conversion," Proc. Inst. Mech. Eng., Part B, **216**(7), pp. 1053–1059.

[6] Chan, W. K., Wong, Y. W., Chua, C. K., Lee, C. W., and Feng, C., 2003, "Rapid Manufacturing Techniques in the Development of an Axial Blood Pump Impeller," Proc. Inst. Mech. Eng., Part H, **217**(6), pp. 469–475.

[7] Quail, F. J., Scanlon, T. J., and Stickland, M. T., 2010, "Development of a Regenerative Pump Impeller Using Rapid Manufacturing Techniques," Rapid Prototyping J., **16**(5), pp. 337–344. AQ8

[8] Galantucci, L. M., Lavecchia, F., and Percoco, G., 2009, "Experimental Study Aiming to Enhance the Surface Finish of Fused Deposition Modeled Parts," CIRP Ann.-Manuf. Technol., **58**(1), pp. 189–192.

[9] Masood, S. H., and Soo, A., 2002, "A Rule Based Expert System for Rapid Prototyping System Selection," Rob. Comput. Integr. Manuf., **18**(3–4), pp. 267–274.

[10] Sun, J., Chen, S., Qu, Y., and Li, J., 2015, "Review on Stress Corrosion and Corrosion Fatigue Failure of Centrifugal Compressor Impeller," Chin. J. Mech. Eng., **28**(2), pp. 217–225.

[11] Naimpally, A. V., and Rosselot, K. S., 2013, *Environmental Engineering: Review for the Professional Engineering Examination*, Springer, New York.

[12] Evans, V., 2013, *Plastics as Corrosion-Resistant Materials: The Commonwealth and International Library: Plastics Division*, Elsevier, ■. AQ9

[13] MakerBot®Industries, 2015, "MakerBot Filaments–ABS," https://www.store.makerbot.com/filament/abs, Last accessed June 27, 2015.

[14] Lan, H., and Ding, Y., 2007, "Price Quotation Methodology for Stereolithography Parts Based on STL Model," Comput. Ind. Eng., **52**(2), pp. 241–256.

[15] Mello, C. H. P., Martins, R. C., Parra, B. R., de Oliveira Pamplona, E., Salgado, E. G., and Seguso, R. T., 2010, "Systematic Proposal to Calculate Price of Prototypes Manufactured Through Rapid Prototyping an FDM 3D Printer in a University Lab," Rapid Prototyping J., **16**(6), pp. 411–416.

[16] Xu, F., Wong, Y. S., and Loh, H. T., 2001, "Toward Generic Models for Comparative Evaluation and Process Selection in Rapid Prototyping and Manufacturing," J. Manuf. Syst., **19**(5), pp. 283–296.

[17] Dixon, S. L., and Hall, C., 2013, *Fluid Mechanics and Thermodynamics of Turbomachinery*, Butterworth-Heinemann, ■. AQ10

[18] Lobanoff, V. S., and Ross, R. R., 2013, *Centrifugal Pumps: Design and Application: Design and Application*, Elsevier, ■.

[19] Karassik, I. J., Messina, J. P., Cooper, P., and Heald, C. C., 2001, *Pump Handbook*, Vol. 3, McGraw-Hill, New York.

[20] Narasimha Murthy, B. S., Ravindran, M., and Radha Krishna, H. C., 1977, "Influence of Surface Roughness on the Performance of a Radial Pump Impeller," 6th Australasian Hydraulics and Fluid Mechanics Conference.

[21] Varley, F. A., 1961, "Effects of Impeller Design and Surface Roughness on the Performance of Centrifugal Pumps," Proc. Inst. Mech. Eng., **175**(1), pp. 955–989.

[22] Güilich, J. F., 2003, "Effect of Reynolds Number and Surface Roughness on the Efficiency of Centrifugal Pumps," ASME J. Fluids Eng., **125**(4), pp. 670–679.

[23] Ahn, S.-H., Montero, M., Odell, D., Roundy, S., and Wright, P. K., 2002, "Anisotropic Material Properties of Fused Deposition Modeling ABS," Rapid Prototyping J., **8**(4), pp. 248–257.

[24] Bellini, A., and Güçeri, S., 2003, "Mechanical Characterization of Parts Fabricated Using Fused Deposition Modeling," Rapid Prototyping J., **9**(4), pp. 252–264.

[25] Galantucci, L. M., Lavecchia, F., and Percoco, G., 2010, "Quantitative Analysis of a Chemical Treatment to Reduce Roughness of Parts Fabricated Using Fused Deposition Modeling," CIRP Ann.-Manuf. Technol., **59**(1), pp. 247–250.

[26] CERF/IIEC, 2002, Study of Pumps and Fans Market in China. AQ11

[27] Burenin, V. V., and Gaevik, D. T., 1981, "Use of Plastics in Centrifugal Pump Constructions," Chem. Pet. Eng., **17**(2), pp. 69–70.