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Editorial

Editorial on Special Issue "Fatigue and Fracture Behaviour of Additive Manufacturing Mechanical Components"

Roberto Citarella [1,*], Paulo M. S. T. De Castro [2] and Angelo Maligno [3]

1 Department of Industrial Engineering, University of Salerno, 84084 Fisciano, Italy
2 Department of Mechanical Engineering, Universidade do Porto, Faculdade de Engenharia, 4200-465 Porto, Portugal; ptcastro@fe.up.pt
3 Institute for Innovation in Sustainable Engineering, University of Derby, Derby DE 01332, UK; A.Maligno@derby.ac.uk
* Correspondence: rcitarella@unisa.it; Tel.: +39-089-96-4111

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Abstract: This Special Issue presents the latest advances in the field of fatigue and fracture performances of additively manufactured mechanical components, including components made of traditional materials (metals, sintered steels, etc.) but undergoing complex loading conditions (multiaxial fatigue and mixed mode fracture). This Special Issue is composed of seven papers covering new insights in structural and material engineering. The advent of additive manufacturing (AM) processes applied to the fabrication of structural components creates the need for design methodologies and structural optimization approaches that take into account the specific characteristics of the process. While AM processes give unprecedented geometrical design freedom, which can result in significant reductions of component weight (e.g., through part count reduction), they have implications in the fatigue and fracture strength due to residual stresses and microstructural features. This is due to stress concentration effects and anisotropy that still need research. The papers of this Special Issue report on numerical simulation and experimental work, or a combination of both. The application of damage and fracture mechanics concepts, the appraisal of stress concentration effects, and the consideration of residual stresses and anisotropic behaviour are tackled for a range of structural applications from biomedical engineering to aerospace components.

Keywords: fatigue; fracture; additive manufacturing; finite element method (FEM)

Transport systems face great pressure in terms of ever-increasing performance and efficiency while ensuring maximum reliability and controlling costs. Material selection, structural design, and fabrication methods play a central role among many different contributions for achieving those objectives.

The mainly used metallic materials are steel alloys, where the introduction of special alloying may substantially improve performance, while sintered steel alloys are playing an increasingly important role because of their corrosion performance.

The emergence of additive manufacturing (AM) implies that components may become simpler, reducing weight and part count, a trend that is also supported by fabrication techniques such as friction stir welding or laser beam welding, leading to integral structures.

Open problems exist in all those areas, as exemplified by the assurance of integrity and mechanical performance of AM parts. Moreover, the benefits of AM are offset to a certain extent by the poor surface finish and high residual stresses resulting from the printing process, which consequently compromise the mechanical properties of the parts, particularly their fatigue performance.

The understanding of the mechanical behaviour and its incorporation into design practice is made through structural analysis, and this subject is also of interest for this Special Issue. Computational mechanics progressed from the traditional finite element method (FEM) and dual boundary element method (DBEM) approaches to combined/hybrid and multiscale analyses that may accurately model and predict crack paths and damage within controlled computational effort.

The purpose of this Special Issue is to draw the attention of the scientific community to recent advances in modelling and optimizing the structural behaviour of advanced materials and their possible applications, while also considering non-destructive testing and evaluation.

Theoretical, numerical, and experimental contributions describing original research results and innovative concepts on materials and structures were collected.

This Special Issue includes several high-quality papers written by leading and emerging specialists in the field. Among the articles collected, a number of high-quality papers existed, which led to seven published articles. A very short description of the addressed topics, in the order of themes cited below, is presented.

When studying the performance of additively manufactured components, an important issue is related to the correct design of the specimen in fatigue testing. In the property characterization of additive manufacturing materials, mini specimens are preferred due to the specimen preparation and manufacturing cost, but mini specimens demonstrate higher fatigue strength than standard specimens due to the lower probability of material defects resulting in fatigue. In Reference [1], a novel adaptive displacement-controlled test set-up was developed for fatigue testing using mini specimens. In this study, a dual gauge section Krouse type mini specimen was designed to conduct fatigue tests on additively manufactured materials. A fully reversed bending ($R = -1$) fatigue test was performed on simply supported specimens. The fatigue performance of the wrought 304 and additively manufactured 304L stainless steel was compared applying a control signal monitoring (CSM) method. The test results and analyses were useful to validate the design of the specimen and the effective implementation of the test bench in the fatigue testing of additively manufactured materials.

It was proven that surface integrity alteration induced by the machining process or AM has a profound influence on the performance of a component. The different manufacturing conditions directly affect the surface state of the parts (surface texture, surface morphology, surface residual stress, etc.) and affect the final performance of the workpiece.

In particular, with reference to AM, its benefits are offset to a certain extent by the poor surface finish and high residual stresses resulting from the printing process, which consequently compromise the mechanical properties of the parts, particularly their fatigue performance. Ultrasonic impact treatment (UIT) is a surface modification process which is often used to increase the fatigue life of welds in ship hulls and steel bridges. In Reference [2], the benefits of ultrasonic impact treatment (UIT) on the fatigue life of Ti-6Al-4V, manufactured by direct metal laser sintering (DMLS), were illustrated. Results showed that UIT enhanced the fatigue life of DMLS Ti-6Al-4V parts by suppressing the surface defects originating from the DMLS process and inducing compressive residual stresses at the surface. At the adopted UIT application parameters, the treatment improved the fatigue performance by 200%, significantly decreased surface porosity, reduced the surface roughness by 69%, and imposed a compressive hydrostatic stress of 1644 MPa at the surface.

On the other hand, with reference to milling technology, which can process parts of different quality grades according to the processing conditions, it is of great significance to reveal the mapping relationship between working conditions, surface integrity, and part performance for the rational selection of cutting conditions. In Reference [3], the effects of cutting parameters such as cutting speed, feed speed, cutting depth, and tool wear on the machined surface integrity during milling were thoroughly reviewed. At the same time, the relationship between the machined surface integrity and the performance of parts was also revealed. Furthermore, problems that exist in the study of surface integrity and workpiece performance in the milling process were pointed out with the final suggestion that more research should be conducted in this area in the future.

When considering dentistry applications of newly advanced materials, one issue is related to the proper adjustment of crown implant abutment during installation.

In Reference [4], the fracture resistance and stress distribution of zirconia specimens were compared considering four occlusal surface areas of implant abutment. Four implant abutment designs with 15 zirconia prostheses over the molar area per group were prepared for cyclic loading with 5 Hz, 300 N in a servo-hydraulic testing machine until fracture or automatic stoppage after 30,000 counts. Four finite element models were simulated under vertical or oblique 10-degree loading to analyse the stress distribution and peak value of zirconia specimens. Data were statistically analysed, and fracture patterns were observed under a scanning electron microscope. Cyclic loading tests revealed that specimen breakage had moderately strong correlation with the abutment occlusal area ($r = 0.475$). Specimen breakage differed significantly among the four groups ($p = 0.001$). The lowest von Mises stress value was measured for the prosthesis with a smallest abutment occlusal surface area (SA25) and the thickest zirconia crown. Thicker zirconia specimens (SA25) had higher fracture resistance and lowest stress values under 300-N loading.

The second part of this Special Issue is concerned with traditional materials but under complex fatigue conditions, like those generated in rails and wheels undergoing rolling contact fatigue with consequent crack initiations. Such cracks then develop under non-proportional mixed mode I/II/III loading, whose assessment represents a challenge for scientists involved in railway accident prevention.

In Reference [5], fatigue tests were performed to estimate the coplanar and branch crack growth rates on rail and wheel steel under non-proportional mixed mode I/II loading cycles simulating the load on rolling contact fatigue cracks; sequential and overlapping mode I and II loadings were applied to single cracks in the specimens. Long coplanar cracks were produced under certain loading conditions. The fracture surfaces observed by scanning electron microscopy and the finite element analysis results suggested that the growth was driven mainly by in-plane shear mode (i.e., mode II) loading. Crack branching likely occurred when the degree of overlap between these mode cycles increased, indicating that such a degree of enhancement led to a relative increase in the maximum tangential stress range, based on an elasto-plastic stress field along the branch direction, compared to the maximum shear stress. Moreover, the crack growth rate decreased when the material strength increased because this made the crack tip displacements smaller. The branch crack growth rates could not be represented by a single crack growth law since the plastic zone size ahead of the crack tip increased with the shear part of the loading due to the T-stress, resulting in higher growth rates.

In Reference [6], sequential and overlapping mode I and III loading cycles were applied to single cracks in round bar specimens. The fracture surface observations and the finite element analysis results suggested that the growth of long coplanar cracks was driven mainly by mode III loading. The cracks tended to branch when increasing the material strength and/or the degree of overlap between the mode I and III loading cycles. The equivalent stress intensity factor range that could consider the crack face contact and successfully regress the crack growth rate data was proposed for the branch crack. Based on the results obtained in this study, the mechanism of long coplanar shear-mode crack growth turned out to be the same regardless of whether the main driving force was in-plane shear or out-of-plane shear.

The last paper in this Special Issue concerns real components and, in particular, aerospace structures, whose residual life in the presence of a service crack is evaluated.

In Reference [7], the authors presented the results of a systematic crack propagation analysis campaign performed on a compressor-blade-like structure. The point of novelty was that different blade design parameters were varied and explored in order to investigate how the crack propagation rate in low cycle fatigue (LCF, at R ratio R = 0) could be reduced. The design parameters/variables studied in this work were as follows: (1) the length of the contact surfaces between the dovetail root and the disc, and (2) their inclination angle. Effects of the friction coefficient between the disc and the blade root were also investigated. The LCF crack propagation analyses were performed by recalculating the stress field as a function of the crack propagation by using the Fracture Analysis Code (Franc3D®, http://www.fracanalysis.com/Fracture Analysis Consultants, Inc 121 Eastern Heights Dr Ithaca, 14850 New York, NY, USA. Phone: 607-257-4970).

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References

1. Parvez, M.; Chen, Y.; Karnati, S.; Coward, C.; Newkirk, J.; Liou, F. A Displacement Controlled Fatigue Test Method for Additively Manufactured Materials. *Appl. Sci.* **2019**, *9*, 3226. [CrossRef]
2. Walker, P.; Malz, S.; Trudel, E.; Nosir, S.; ElSayed, M.; Kok, L. Effects of Ultrasonic Impact Treatment on the Stress-Controlled Fatigue Performance of Additively Manufactured DMLS Ti-6Al-4V Alloy. *Appl. Sci.* **2019**, *9*, 4787. [CrossRef]
3. Yue, C.; Gao, H.; Liu, X.; Liang, S. Part Functionality Alterations Induced by Changes of Surface Integrity in Metal Milling Process: A Review. *Appl. Sci.* **2018**, *8*, 2550. [CrossRef]
4. Lan, T.; Pan, C.; Liu, P.; Chou, M. Fracture Resistance of Monolithic Zirconia Crowns on Four Occlusal Convergent Abutments in Implant Prosthesis. *Appl. Sci.* **2019**, *9*, 2585. [CrossRef]
5. Akama, M. Fatigue Crack Growth under Non-Proportional Mixed Mode Loading in Rail and Wheel Steel Part 1: Sequential Mode I and Mode II Loading. *Appl. Sci.* **2019**, *9*, 2006. [CrossRef]
6. Akama, M.; Kiuchi, A. Fatigue Crack Growth under Non-Proportional Mixed Mode Loading in Rail and Wheel Steel Part 2: Sequential Mode I and Mode III Loading. *Appl. Sci.* **2019**, *9*, 2866. [CrossRef]
7. Canale, G.; Kinawy, M.; Maligno, A.; Sathujoda, P.; Citarella, R. Study of Mixed-Mode Cracking of Dovetail Root of an Aero-Engine Blade Like Structure. *Appl. Sci.* **2019**, *9*, 3825. [CrossRef]