metals

Editorial

Technological Aspects in Fatigue Design of Metallic Structures

Martin Leitner

Institute of Structural Durability and Railway Technology, Graz University of Technology, 8010 Graz, Austria; martin.leitner@tugraz.at

1. Introduction and Scope

Traditional manufacturing processes, such as welding and casting, and modern techniques, such as additive manufacturing, can significantly affect the local material properties of metallic materials. To ensure the safe and reliable operation of engineering components and structures, fundamental knowledge of manufacturing effects on fatigue performance is of the utmost importance. Hence, this Special Issue focuses on the fatigue design of metallic structures, considering the influence of technological aspects. Approaches based on local stress/strain, as well as fracture-mechanics-based concepts are applied, considering local manufacturing-process-dependent characteristics, such as microstructure, hardness, porosity/defects, surface topography, and/or residual stress state. Moreover, probabilistic methods are utilized which enable a link between statistically distributed local characteristics and failure/survival probability, enabling the advanced fatigue design of metallic structures.

2. Contributions

Ten papers have been published dealing with different manufacturing processes, such as welding, casting, and additive manufacturing as well as post-treatments, applying various fatigue design concepts ranging from a stress-based fatigue assessment to the fracture mechanical crack growth. Subsequently, an overview of the contributions is given:

In [1], the local characteristics of welded joints are characterized by digital scanning. Particular focus is laid on fillet welds of S700 high-strength steel T-joints, and corresponding fatigue test results are given. In the course of the scanning methodology, the plate angle, weld toe radius, and angle, as significant local weld geometry parameters, are measured and implemented in numerical analyses, which act as inputs for an elaborated probabilistic fatigue model. This model was then utilized to assess an adequate scanning sampling resolution to accurately predict the failure probability of welded joints.

The study presented in [2] focuses on an assessment of the fatigue life of notched specimens with geometries and microstructure representative of welded steel joints. Thereby, welded and non-welded specimens exhibiting different artificially notched geometries, which are located in varying material zones, are investigated. Applying fracture mechanics to assess the crack growth, it is shown that the total fatigue life can be realistically predicted, whereas the estimation of the lifetime until macroscopic crack initiation is more uncertain in the case of sharply notched specimens in comparison to mild notches. Further evaluations regarding the effect of the applied notch stress range on the short and long fatigue crack initiation to fracture ratio as well as correlations between the slope of the S-N curve and the notch acuity are given, therefore contributing to a holistic investigation of the fatigue behavior of welded steel joints as a basis for further design.

The study presented in [3] deals with an analysis of the fatigue strength of repaired welded joints considering both low- and high-strength steels. Specimens were cyclically pre-cracked and the cracks were detected by non-destructive testing (NDT) by applying penetrant and magnetic testing. Afterwards, the fatigue cracks were repaired by removing the material around the crack and further re-welding with a gas metal arc weld process.

Citation: Leitner, M. Technological Aspects in Fatigue Design of Metallic Structures. *Metals* **2023**, *13*, 610. https://doi.org/10.3390/met13030610

Received: 13 March 2023
Accepted: 16 March 2023
Published: 18 March 2023

Investigations of the microstructure and hardness revealed no major difference between the state before and after repairing. Moreover, the stress concentration factor was significantly lower in the case of the repaired specimens due to smaller flank angles. The experiments finally show that almost all repaired specimens reached at least the fatigue life span of the original condition, and for all cases, the corresponding fatigue class of the IIW recommendations was achieved.

Another study [4] demonstrated a damage-based assessment of the fatigue crack initiation site in high-strength steel welded joints which were post-treated by the High Frequency Mechanical Impact (HFMI) treatment technique. Comprehensive experimental investigations involving fatigue tests and X-ray diffraction residual stress measurements in order to analyze the effect of peak stresses in variable amplitude loads on the resulting residual stress state and crack location are performed. The results show that high peak stresses lead to a significant reduction of the beneficial compressive stresses and varying crack initiation sites depending on the level of peak stress occurring. For a detailed assessment, a numerical simulation considering the measured residual stress field, fatigue loading, HFMI weld geometry, and non-linear material behavior was set up, and the local stress/strain was used to evaluate the damage parameter using Smith, Watson, and Topper's method (SWT), which was utilized to identify the critical failure location. It was concluded that the numerical results confirmed the experiments.

A final analysis in regard to welding as a manufacturing process is presented in [5], showing a holistic view on design implications and opportunities of considering fatigue strength, manufacturing variations, and predictive life-cycle costs (PLCC) in welded structures. Based on different design cases and scenarios, the study concludes that welding and production costs are negligible in relation to re-occurring repair costs for all the considered design cases and fatigue scenarios. Further, repair and maintenance costs are higher compared to operational costs for the more severe fatigue scenarios considered. Moreover, it was shown that for welded box structures, increased flange plate thicknesses are most effective to reduce life-cycle costs, as it can increase the intervals between repairs significantly. The paper therefore highlights the importance of incorporating manufacturing variations in an early design stage to ensure an overall minimized life-cycle cost.

The study in [6] emphasizes the effects of residual stress state, surface roughness, and peak load on the micro-cracking of the base material, with a particular focus on sandblasted S690 high-strength steel plates. A two-dimensional finite-element model is developed to cover the measured surface topography and residual stress state. Furthermore, a ductile fracture criterion considering stress triaxiality is applied in order to assess local damage. The results show that under peak load conditions, surface roughness exhibits a dominant influence on micro-crack formation compared to the effects of the residual stress state. It is further concluded that the effect of peak load range on damage formation and crack size is significantly higher than the influence of the residual stress condition. Hence, this paper scientifically contributes to the elaborated investigation of local manufacturing-process-induced properties, such as surface roughness and residual stress, on the damage behavior of high-strength steel plates, which are widely used in engineering metallic structures.

A probabilistic fatigue assessment of surface layers in EN AC-46200 sand castings is presented in [7]. Comprehensive investigations involving areal surface topography scans, microstructural analyses, fatigue tests covering as-cast and hot isostatically pressed (HIP) specimens, as well as detailed fracture surface inspections to determine the local fatigue crack origin, were performed. An advanced fatigue model based on a neural network covering both surface topography notch effect and its interaction with local defects/pores in the surface layer was applied, and validation with the experiments revealed the sound applicability of the probabilistic fatigue approach.

A further study, [8], investigates the same aluminum cast alloy, but is focused on the statistical size effect due to internal defects in the bulk material. Based on numerous fatigue tests incorporating two specimen types with different highly stressed volumes, the probability of occurrence of critical defect sizes and corresponding parameters to set up a generalized extreme value distribution are defined. Furthermore, a probabilistic fatigue design model applying the fracture-mechanics-based Kitagawa–Takahashi approach is presented, leading to a local Weibull factor depending on the return period of the highly stressed volume and the statistically distributed defect population. A final comparison of the fatigue model and the experiments shows a sound agreement and verifies the applicability of the presented approach to cover the statistical size effect in fatigue design.

The fatigue behavior of wire and arc additively manufactured (WAAM) titanium alloy Ti-6Al-4V is investigated in [9]. Fatigue tests and fracture surface analyses highlight that pores/defects in the bulk material and at the surface are the cause for fatigue crack initiation. Therefore, a fracture-mechanics-based fatigue model covering both failure types by a stress intensity equivalent value is developed which considers the manufacturing-process-dependent defect sizes by means of an extreme value distribution by Gumbel. The results reveal that the modified approach using the introduced stress intensity equivalent parameter leads to an improved probabilistic fatigue assessment of both fatigue life as well as strength, and is therefore well applicable for the fatigue design of WAAM Ti-6Al-4V parts.

In the final study [10] of this Special Issue, the microstructural impact on the fatigue crack growth behavior of the alloy 718, which is commonly used for forged structural components in the aircraft industry, is explored. Dependent on the manufacturing process route, different material series are produced, exhibiting varying microstructures characterized by grain-size parameters and strength. Based on the results of numerous fatigue crack propagation tests, it is concluded that the threshold of stress-intensity factor range depends only on grain size and is mainly governed by roughness-induced crack closure. This outcome once more proves the significant effect of local manufacturing-process-induced characteristics on the fatigue performance of metallic materials.

3. Conclusions and Outlook

The scientific contributions in this Special Issue present comprehensive investigations in regard to technological effects on the fatigue behavior of different metallic materials. Based on the results, it is shown that local manufacturing-process-dependent characteristics, such as microstructure, hardness, porosity/defects, surface topography, and/or residual stress state can significantly impact the fatigue performance and need to be considered in the fatigue design. To statistically cover these influences, it is shown that probabilistic approaches are suitable and can lead to an accurate fatigue assessment if the model parameters are well defined. As a future research direction, further work may focus on the interaction of several fatigue-influencing parameters to holistically consider technological aspects in the fatigue design of metallic structures and set up proper fatigue assessment approaches.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Hultgren, G.; Myrén, L.; Barsoum, Z.; Mansour, R. Digital Scanning of Welds and Influence of Sampling Resolution on the Predicted Fatigue Performance: Modelling, Experiment and Simulation. *Metals* **2021**, *11*, 822. [CrossRef]
2. Braun, M.; Fischer, C.; Baumgartner, J.; Hecht, M.; Varfolomeev, I. Fatigue Crack Initiation and Propagation Relation of Notched Specimens with Welded Joint Characteristics. *Metals* **2022**, *12*, 615. [CrossRef]
3. Schubnell, J.; Ladendorf, P.; Sarmast, A.; Farajian, M.; Knödel, P. Fatigue Performance of High- and Low-Strength Repaired Welded Steel Joints. *Metals* **2021**, *11*, 293. [CrossRef]
4. Ono, Y.; Yıldırım, H.C.; Kinoshita, K.; Nussbaumer, A. Damage-Based Assessment of the Fatigue Crack Initiation Site in High-Strength Steel Welded Joints Treated by HFMI. *Metals* **2022**, *12*, 145. [CrossRef]
5. Hagnell, M.K.; Khurshid, M.; Åkermo, M.; Barsoum, Z. Design Implications and Opportunities of Considering Fatigue Strength, Manufacturing Variations and Predictive LCC in Welds. *Metals* **2021**, *11*, 1527. [CrossRef]
6. Nafar Dastgerdi, J.; Sheibanian, F.; Remes, H.; Hosseini Toudeshky, H. Influences of Residual Stress, Surface Roughness and Peak-Load on Micro-Cracking: Sensitivity Analysis. *Metals* **2021**, *11*, 320. [CrossRef]
7. Pomberger, S.; Oberreiter, M.; Leitner, M.; Stoschka, M.; Thuswaldner, J. Probabilistic Surface Layer Fatigue Strength Assessment of EN AC-46200 Sand Castings. *Metals* **2020**, *10*, 616. [CrossRef]
8. Oberreiter, M.; Pomberger, S.; Leitner, M.; Stoschka, M. Validation Study on the Statistical Size Effect in Cast Aluminium. *Metals* **2020**, *10*, 710. [CrossRef]

9. Springer, S.; Leitner, M.; Gruber, T.; Oberwinkler, B.; Lasnik, M.; Grün, F. Fatigue Assessment of Wire and Arc Additively Manufactured Ti-6Al-4V. *Metals* **2022**, *12*, 795. [CrossRef]
10. Gruber, C.; Raninger, P.; Maierhofer, J.; Gänser, H.-P.; Stanojevic, A.; Hohenwarter, A.; Pippan, R. Microstructural Impact on Fatigue Crack Growth Behavior of Alloy 718. *Metals* **2022**, *12*, 710. [CrossRef]