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Article

Integrated Fatigue and Vibration Design of Medical Welded Rotating Structures

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Abstract: An integrated design framework combining fatigue life prediction and vibration analysis is developed for medical welded rotating structures. Residual stress fields obtained from welding simulations were coupled with harmonic vibration analysis under rotational excitation. A case study involving a welded rotating component subjected to 600 rpm operation showed that regions with high residual tensile stress also experienced amplified dynamic stress responses. Design optimization reduced combined fatigue-vibration damage by 29.7%, highlighting the necessity of joint consideration of welding and dynamic effects in medical device design.

Keywords: medical welded structures; fatigue-vibration coupling; residual stress; rotating components; integrated design

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1. Introduction

Medical welded rotating structures, including rotating frames, drive-side supports in imaging gantries and precision rotating subassemblies, are required to operate reliably over long service periods under strict safety and performance constraints [1,2]. Welded joints are widely adopted in such systems because they provide high structural stiffness, compact layouts, and efficient manufacturability. However, welding processes inevitably introduce local stress concentration, material non-uniformity, and residual deformation, which strongly influence crack initiation and fatigue damage under high-cycle operating conditions [3]. In recent years, fatigue-related research on welded components has mainly progressed along three directions: characterization of welding-induced residual stress, fatigue assessment of welded joints under complex loading, and vibration-driven stress evaluation of rotating structures [4]. Despite these advances, these aspects are often treated independently, which limits their applicability to medical rotating devices where welding effects and operational dynamics coexist.

Residual stress plays a central role in linking welding processes to fatigue performance. Experimental and numerical studies have demonstrated that tensile residual stress at weld toes and roots can significantly reduce fatigue resistance even under moderate nominal stress ranges, primarily through its influence on effective mean stress and crack driving force [5]. To improve prediction reliability, various approaches have been proposed for residual stress quantification and validation, including calibrated thermo-mechanical welding simulations and diffraction-based measurement techniques [6,7]. In parallel, investigations on rotating medical devices have shown that vibration response and unbalance-related dynamic loading can interact strongly with local structural characteristics, indicating that vibration performance cannot be evaluated independently of weld-induced stress states [8]. These findings highlight the need for integrated analysis frameworks that consider both residual stress and dynamic excitation in medical rotating structures.

Advances in thermo-mechanical welding simulation have further improved the prediction accuracy of residual stress fields by incorporating refined heat source models and material-dependent constitutive behavior [8]. Such simulations enable spatially resolved stress fields to be introduced into subsequent structural and fatigue analyses, rather than relying on simplified uniform stress assumptions. Experimental evidence, however, indicates that residual stresses are not static during service. Cyclic loading may partially relax or redistribute welding residual stress, depending on load amplitude, material response, and local constraint conditions [9]. As a result, different assumptions regarding residual stress evolution can lead to substantially different fatigue life predictions, especially in welded regions subjected to combined static and dynamic loading. Fatigue assessment methods for welded joints have also evolved toward improved treatment of mean stress effects, multiaxial loading, and variable amplitude conditions. Structural stress, notch stress, and fracture-mechanics-based approaches have been systematically compared with respect to their applicability to welded details and post-weld treatment scenarios [10,11]. Experimental studies further demonstrate that mean stress and load sequence effects can significantly alter fatigue life even when equivalent stress measures are similar [12]. Unified fatigue design frameworks have been proposed to improve consistency between as-welded and stress-relieved conditions while maintaining compatibility with existing design codes [13]. In addition, multiaxial fatigue assessment has received increasing attention, particularly for welded joints subjected to combined bending and torsion, with practical evaluation strategies aligned with modern fatigue standards [14]. Nevertheless, many fatigue analyses still rely on simplified residual stress representations rather than spatially resolved stress fields derived from welding simulations or measurements.

Vibration-induced fatigue represents another critical concern for welded rotating structures. In many applications, fatigue damage is governed not by static loading but by resonant or near-resonant dynamic response. Frequency-domain fatigue methods, including power spectral density-based approaches, have gained increasing popularity because of their ability to account for modal contributions with reasonable computational efficiency [15]. These methods are often combined with finite element modal and harmonic analyses to estimate dynamic stress responses under operational excitation [16]. For rotating systems, rotor-dynamic studies emphasize the influence of imbalance, gyroscopic effects, and operating speed on harmonic stress amplitudes and fatigue risk [17]. Investigations on rotating shafts and welded assemblies further indicate that bending-torsion interaction can substantially alter fatigue life predictions [18]. Despite these developments, vibration-fatigue analyses frequently neglect welding-induced residual stress or represent welded joints using simplified stress concentration factors that do not reflect local stiffness variation and tensile stress bias. These limitations are particularly pronounced in medical welded rotating components. Such devices often operate at fixed or narrowly distributed rotational speeds, making them highly sensitive to harmonic excitation. When excitation frequencies approach structural modes, dynamic stress amplification may dominate fatigue damage. In welded rotating structures, regions with high tensile residual stress frequently coincide with areas of elevated dynamic stress response due to geometric discontinuities and local compliance. Recent studies confirm that residual tensile stress can markedly shorten fatigue life in high-performance welded components used in precision medical equipment. At the same time, the lack of standardized fatigue datasets and integrated assessment procedures continues to hinder the development of unified design guidelines [19]. Practical challenges, such as limited strain measurement coverage and the difficulty of translating vibration data into local damage estimates, further motivate simulation-based design approaches [20].

In this study, we establish an integrated fatigue-vibration design framework for medical welded rotating structures. Residual stress fields obtained from thermo-mechanical welding simulations are coupled with harmonic vibration analysis under rotational excitation, enabling spatially consistent evaluation of fatigue-relevant stress responses in weld-affected regions. Established fatigue assessment principles are retained while residual stress effects are explicitly incorporated throughout the analysis process. A representative case study at an operating speed of 600 rpm shows that regions exhibiting high tensile residual stress also experience pronounced dynamic stress amplification under harmonic loading. Design optimization targeting both welded joints and vibration-sensitive regions leads to a clear reduction in combined fatigue-vibration damage, providing a practical basis for early-stage structural design of medical rotating devices in which welding effects and dynamic behavior must be considered simultaneously to ensure long-term reliability.

2. Materials and Methods

2.1. Sample Description and Study Object

The study examined a welded rotating component used in medical imaging and precision rotation systems. Twelve specimens were analyzed, including eight welded samples and four non-welded samples used as references. All welded specimens were manufactured from medical-grade stainless steel by gas tungsten arc welding under controlled fabrication conditions. The specimens had the same geometry, dimensions, and boundary interfaces to avoid geometric bias. The component was designed for steady operation at 600 rpm, which reflects typical working conditions in medical devices. Weld seams were located in regions subjected to combined bending and centrifugal loads, where fatigue damage is more likely to initiate.

2.2. Experimental Design and Control Setup

The specimens were divided into an experimental group and a control group to examine the influence of welding on fatigue behavior under vibration. The experimental group consisted of welded specimens in the as-welded condition. The control group consisted of non-welded specimens with identical geometry and material properties. Both groups were analyzed under the same rotational speed, loading conditions, and boundary constraints. This design ensured that differences in stress response were mainly caused by welding-induced effects rather than external factors. The comparison provided a clear reference for evaluating the combined influence of welding residual stress and dynamic loading.

2.3. Measurement Methods and Quality Control

Residual stress fields in welded specimens were obtained using thermo-mechanical welding simulations based on established material models and welding parameters. Dynamic stress responses were calculated through finite element harmonic analysis under rotational excitation. A refined mesh was applied in weld-affected areas to capture local stress variations. Mesh convergence was checked by comparing stress results from different mesh densities. All simulations used the same material properties, damping assumptions, and boundary conditions. Input data and numerical results were reviewed to prevent non-physical stress peaks caused by modeling or discretization errors.

2.4. Data Processing and Mathematical Formulation

Local stress data were processed by combining residual stress with dynamic stress amplitude. The equivalent stress range used for fatigue evaluation was defined as

$$\Delta\sigma_{eq}=\sigma_{dyn}+\sigma_{res},$$

where σ_{dyn} is the stress amplitude from vibration analysis and σ_{res} is the local residual tensile stress from welding. Fatigue damage was estimated using a linear accumulation rule, expressed as

$$D=\sum_{i=1}^{n}\frac{N_i}{N_f(\Delta\sigma_{eq,i})},$$

where N_i is the number of applied cycles at stress level i, and N_f is the fatigue life corresponding to the same stress range. This approach allowed direct comparison of fatigue damage among different structural configurations.

2.5. Fatigue-Vibration Assessment and Design Adjustment

Fatigue damage results were mapped onto the structural model under operating conditions. Areas showing both high residual stress and high dynamic stress were identified as critical locations. Structural adjustments were then applied by modifying local weld geometry and stiffness distribution while keeping the total mass unchanged. Each modified design was evaluated using the same fatigue damage calculation procedure. This process allowed the influence of structural changes on vibration response and fatigue performance to be assessed in a consistent manner, supporting early-stage design optimization.

3. Results and Discussion

3.1. Residual Stress Distribution and Fatigue-Critical Locations

The welding simulation showed a tensile-dominated residual stress zone near the weld toe. Peak tensile values appeared mainly in the transition between the weld metal and the heat-affected zone rather than at the weld centerline. When the residual stress field was combined with the rotating-load stress results, the same region also exhibited the highest local stress gradient. This overlap indicates that the weld toe acted as both a stress raiser and a mean-stress source. As a result, fatigue-sensitive locations were governed by the interaction of geometry and residual stress, not by nominal loading alone. Similar observations have been reported in recent studies, where tensile residual stress was found to control fatigue crack initiation even under moderate external loads [20]. In the present case, the initial fatigue hot spot coincided with the tensile residual-stress band once rotational loading was applied. This behavior supports the use of spatially resolved residual-stress fields instead of uniform stress offsets in fatigue assessment. Figure 1 illustrates a typical residual-stress characterization approach used in recent literature and served as a reference for stress-field interpretation in this study.

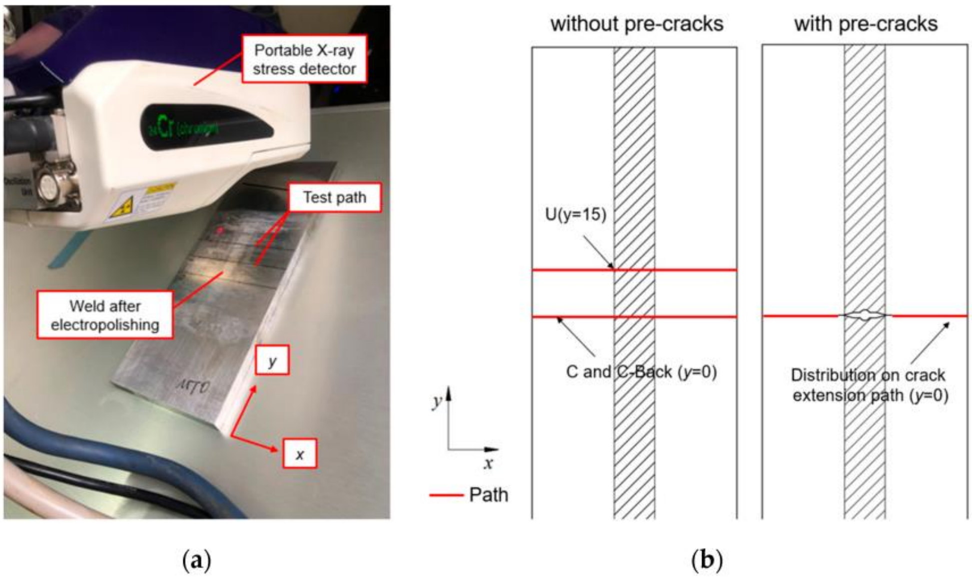

Figure 1. Residual stress near the weld toe, with tensile stress concentrated in the heat-affected zone.

3.2. Dynamic Stress Response under Rotational Excitation

The harmonic analysis performed at 600 rpm showed that dynamic stress was unevenly distributed across the structure. Stress peaks followed the modal deformation path and passed directly through weld-adjacent regions. The dominant response appeared in the low-frequency range, where structural flexibility was highest. At these frequencies, the dynamic stress amplitude at the weld toe was noticeably higher than that of the non-welded reference model. Since both models shared the same geometry and boundary conditions, this difference cannot be attributed to structural layout alone. Instead, it reflects the combined influence of weld-local stiffness variation and residual-stress-biased mean stress. Previous vibration-fatigue studies have shown that local stress response is a more reliable damage indicator than global excitation level, especially near resonant conditions [21]. Figure 2 is cited as a methodological reference illustrating why frequency-domain stress response must be evaluated carefully when vibration governs fatigue behavior.

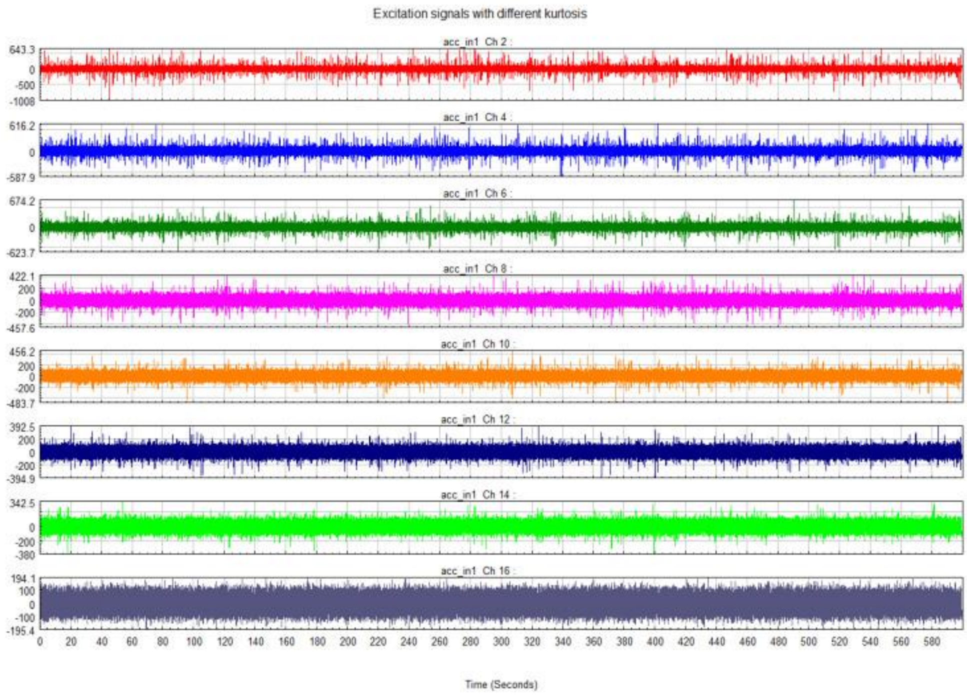

Figure 2. Dynamic stress response of the rotating structure at 600 rpm, with increased stress along the dominant vibration mode.

3.3. Coupled Fatigue-Vibration Damage and Comparison with Previous Studies

When residual tensile stress and dynamic stress amplitude were combined, the highest damage values appeared at the weld toe. In several locations, the dynamic stress alone was not the maximum, yet the coupled damage index was elevated due to the presence of tensile residual stress. This result shows that residual stress altered the relative ranking of fatigue-critical points by increasing the effective mean stress and reducing the allowable stress range. Similar conclusions have been reported in recent fatigue studies, where neglecting welding residual stress led to non-conservative life predictions [22]. In the present analysis, locations within the tensile residual-stress band accumulated damage more rapidly per cycle, even under comparable vibration amplitudes. This finding explains why vibration-only evaluation may underestimate fatigue risk in welded rotating structures. It also confirms that residual stress and vibration should be treated together rather than as independent factors.

3.4. Design Optimization Results and Engineering Implications

The optimization strategy focused on reducing both local dynamic stress concentration and its overlap with tensile residual-stress zones. After optimization, the combined fatigue-vibration damage index decreased by 29.7%. In addition, the dominant stress hot spot shifted away from the weld toe toward a region with lower notch sensitivity. This shift is particularly important for medical rotating devices, which often operate at constant speed and experience repeated cyclic loading over long service periods. From an engineering perspective, the results show that small adjustments in weld geometry and local stiffness can produce a larger benefit than measures targeting fatigue or vibration alone. The coupled assessment therefore provides a more effective basis for early-stage design decisions, where welding layout and dynamic response must be evaluated together to improve long-term reliability.

4. Conclusion

This work developed an integrated fatigue and vibration design method for medical welded rotating structures by linking welding residual stress with harmonic vibration analysis under operating rotation. The results show that tensile residual stress near welds often overlaps with vibration-induced stress increase, which raises local fatigue damage beyond what is predicted by separate fatigue or vibration checks. The combined assessment allowed fatigue-critical regions to be identified more reliably and guided focused structural adjustment. The case study confirmed that modifying weld geometry and local stiffness together can reduce combined fatigue-vibration damage, rather than relying on single-factor tuning. From a scientific viewpoint, the study clarifies how welding residual stress governs vibration-driven fatigue behavior in rotating welded components and provides a practical way to include process-related effects in dynamic design. The proposed method is suitable for early design stages of medical devices operating at fixed or narrow speed ranges, where repeated cyclic loading is unavoidable. The study is limited to steady-speed conditions and simulation-based residual stress input. Further work should include variable-speed operation, experimental verification, and residual stress evolution under cyclic loading to improve prediction reliability.

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