

Application of Linear Friction Welding Technique to Aircraft Engine Parts

KUROKI Hiroshi : General Manager, Engine Technology Department, Research & Engineering Division, Aero-Engine & Space Operations
NEZAKI Koji : General Manager, Welding Technology Department, Production Engineering Center, Corporate Research & Development
WAKABAYASHI Tsukasa : Manager, Production Planning Department, Manufacturing Division, Aero-Engine & Space Operations
NAKAMURA Kenji : Manager, Production Planning Department, Manufacturing Division, Aero-Engine & Space Operations

In recent aircraft engines, the application of blisks in fan and compressor rotors is increasing to achieve weight reduction and performance improvement. The conventional manufacturing method of blisks is to machine them from a forged material. But with this method, the loss of material is relatively large. Therefore a manufacturing method in which blades are joined to disks with Linear Friction Welding (LFW) is being developed. LFW is a kind of solid state welding technique in which the weld surfaces are rubbed together to cause them to heat up. In the current study, the changes in the micro structure, the structural integrity of the LFW joint, and the results of the manufacturing trial of the compressor blisk are reported.

1. Introduction

In aircraft jet engines, blisks, which are integrated blades and disks, are increasingly being adopted in fan and compressor rotors for the purpose of lighter weight and performance improvement. Weight reduction is achieved by reducing the weight of the joints between blades and disk as well as the weight of the disk bore that supports the joints, and performance improvement is achieved by reducing air leakage from gaps between the platforms of the blades. **Figure 1** illustrates a comparison of a conventional blade/disk structure versus a blisk structure. Typically, weight can be reduced by approximately 20% by adopting the blisk structure.

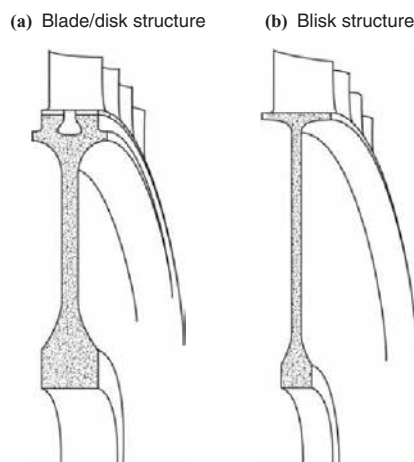


Fig. 1 Comparison of compressor disk structure⁽¹⁾

Blisk manufacturing typically involves machining blades from a forged material. Expensive titanium alloys are often used for the fan, compressor disk, and blade material, and if blisks are manufactured by machining, much material is wasted in the form of shavings during the crude processing stage. In order to solve this problem, a method of manufacturing blisks using Linear Friction Welding (LFW) has been proposed, and is being put into practical use in applications such as fighter aircraft engines. LFW is a technology for manufacturing blisks by welding blade parts to separately manufactured disks. **Figure 2** illustrates a schematic view of blisk manufacturing by LFW.

LFW is a technology that achieves a weld by pushing one part onto another part and producing frictional heat by moving one of the parts back and forth parallel to the weld

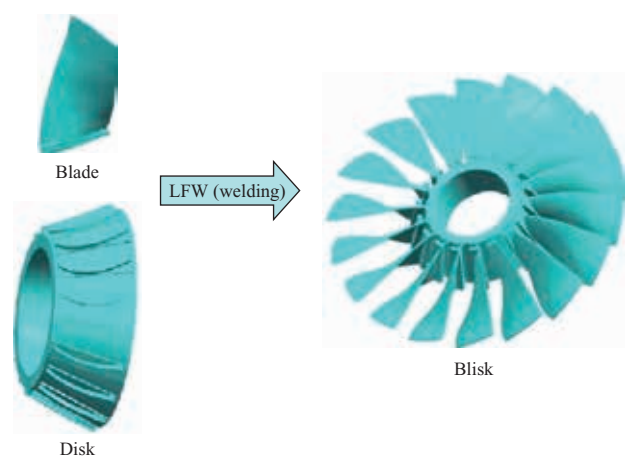


Fig. 2 Schematic view of blisk manufacturing by LFW

surface. **Figure 3** illustrates a schematic view of an LFW process. LFW is a type of solid-state welding that consistently obtains a better joint structure than fusion welding, and thus is suited to blisk manufacturing, which demands high reliability. In addition, LFW allows a high degree of freedom in joint shape, making it superior to rotational friction welding, which is limited to axisymmetric shapes.

In this study, the metallographic changes and mechanical properties of an LFW joint as well as the results of a blisk manufacturing trial are reported.

2. Welding of test specimens

2.1 Test conditions

In order to investigate the metallographic changes and mechanical properties of the joint, a welding test was performed on test specimens with rectangular cross-sections having the same weld interface cross-sectional area as an actual compressor rotor. The material of the test specimens was Ti-6Al-4V alloy (AMS4928), a material commonly used for fans, compressor disks, and blades.

The effects of the magnitude of the load were investigated. With weld load P defined as the reference load, welding was performed with up to three times that load, and the hardness distribution, macro/micro structure observations, Ultimate Tensile Strength (UTS), and fatigue strengths of

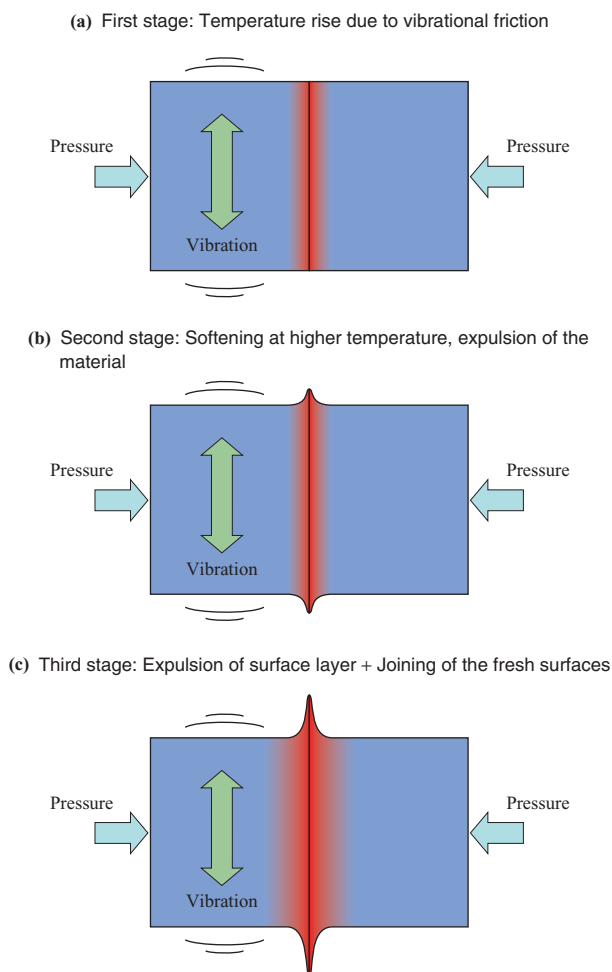


Fig. 3 Schematic view of LFW process

the joints were examined.

2.2 Structure observation

Figure 4 illustrates the macrostructure of the LFW joints. The combined width of the weld interface and the Thermo-Mechanically Affected Zone (TMAZ) is slightly broader at lower weld loads, yielding 1.5 mm at $1P$ and 0.8 mm at $3P$. This is because the material is subjected to a higher temperature for a longer duration. When the weld load is low, the material strength needs to be lower to start plastic deformation. Therefore the temperature needs to be higher. As a result, it takes more time to heat and the frictional heat spreads farther.

Figure 5 illustrates the microstructure of a parent material. Forgings of Ti-6Al-4V alloy are known to have an α and β

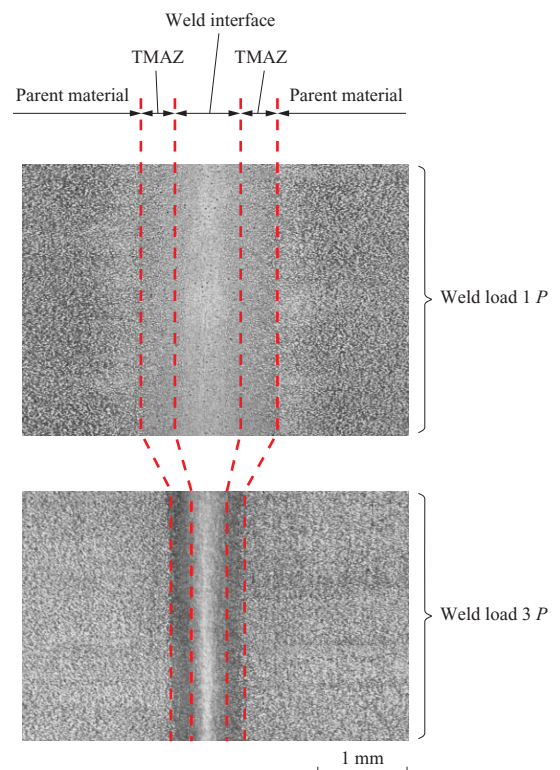


Fig. 4 Macrostructure of LFW joints

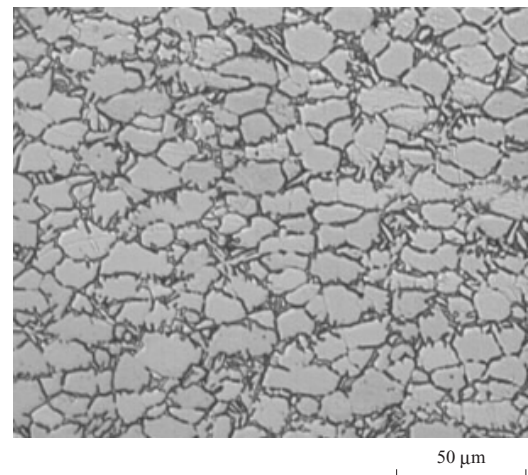


Fig. 5 Microstructure of parent material

Bimodal structure. In contrast, as **Fig. 6** illustrates, the microstructure of the weld interface exhibits a very fine, needle-like α structure, with the structure becoming finer under greater weld loads. The Ti-6Al-4V alloy undergoes β transformation at high temperature, and it can be confirmed that the β transformation temperature is exceeded at the joint.

Also, the results of hardness measurements show that the joints hardened. The micro structure change within the material is also thought to be a contributory factor. **Figure 7** illustrates the distribution of the hardness.

2.3 Mechanical property test

The test specimens were cut from the joints and subjected to tensile and fatigue tests. The test specimens were not heat treated for residual stress removal. Whether a difference in tensile strength was present between the center and ends of the test specimens was checked. **Figure 8** illustrates the results of the tensile test (UTS comparison). It was

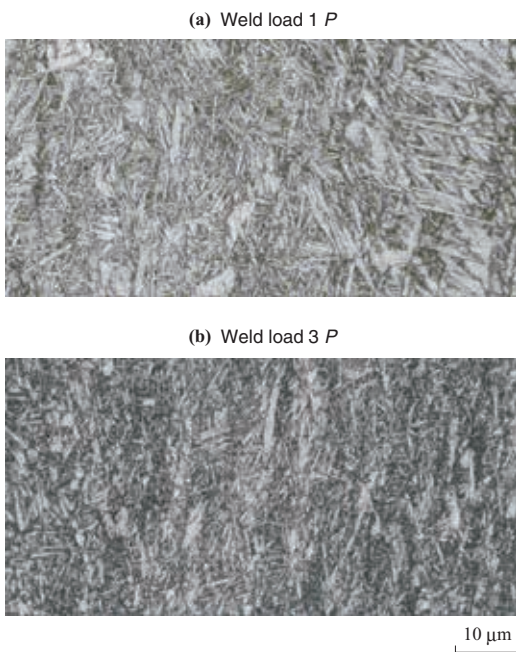


Fig. 6 Microstructure of LFW weld line

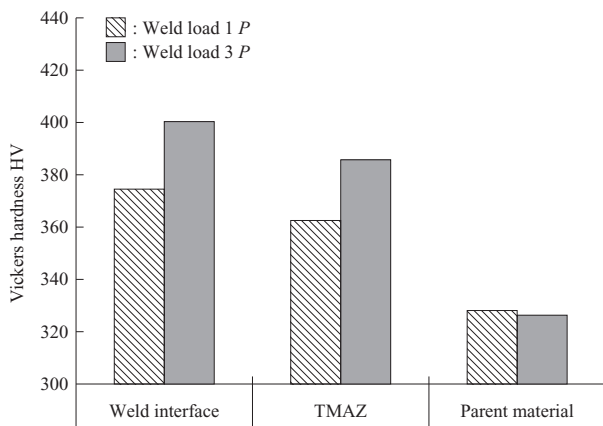


Fig. 7 Distribution of the hardness

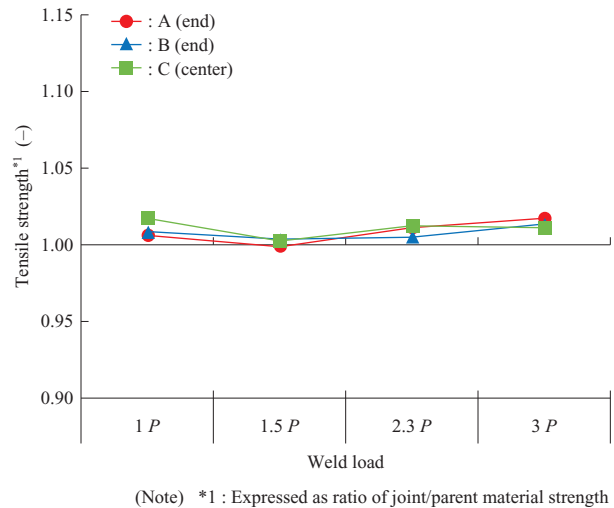


Fig. 8 UTS of LFW joints

confirmed that there was no difference in strength dependent upon the location in the test specimen or weld load of the test specimens. There is a fracture site in the parent material rather than the joint, and that is thought to represent the strength of the parent material.

Figure 9 illustrates the results of the fatigue test (fatigue strength of LFW joints). It was confirmed that there was no significant difference in fatigue strength dependent upon the weld load. However, other researchers have identified some influencing factors,⁽²⁾ so our evaluation of joint fatigue strength was performed carefully. Details are given in **Section 3.2**.

3. Blisk manufacturing trial

3.1 Dimensional precision

In order to verify blisk manufacturability, a manufacturing trial of an actual-sized compressor blisk was conducted (**Fig. 10**). LFW was performed by oscillating and pushing blades onto a disk. The blades have gripping flanges that allow them to be securely held during the oscillation. The weld line was positioned a distance away from the airfoil root fillet to avoid stress concentration.

After the welding was finished, the positions of the blade tips were measured with a three-dimensional measuring machine to check the dimensional precision. When measured

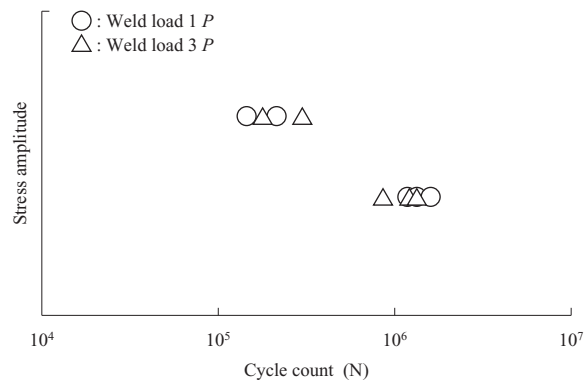


Fig. 9 Fatigue strength of LFW joints



Fig. 10 Compressor blisk manufactured by LFW⁽³⁾

figures were converted to blade inclinations, the variation was approximately 0.04 degrees in the spanwise direction. This corresponds to a displacement of 0.07 mm for blades with a height of 100 mm, which is well within the tolerance range, demonstrating sufficient manufacturability. Figure 11 illustrates the measurement results of the variation in LFW joint inclination.

3.2 High cycle fatigue test on actual blades

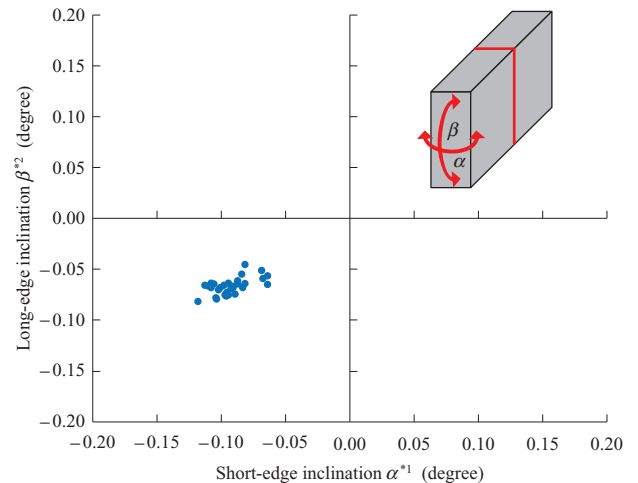
For compressor blades, the major failure mode is High Cycle Fatigue (HCF). In order to check whether blades welded by LFW exhibit the required HCF strength for real-world applications, a vibration test was performed on actual blades.

In the most basic primary bending mode, a peak in the vibratory stress occurs at the airfoil root fillet, thus the weld site was set so as to avoid the peak stress. Pre-test strain distribution measurements show a strain distribution that matches well with Finite Element Method (FEM) analysis, demonstrating that the welding does not produce changes in the vibratory properties. Figure 12 illustrates the vibratory stress distribution of an HCF test specimen. The test results confirmed that blades welded by LFW exhibited the required HCF strength for real-world applications.

4. Conclusion

The microstructure and mechanical properties of LFW joints made of the Ti-6Al-4V alloy commonly used for the fans and compressors of jet engines were investigated. The structure of the weld interface is primarily a needle-like α structure, slightly harder than the parent material, and the tensile strength is at least equal to the parent material. The joint strength is largely unaffected over a broad range of weld loads from 1 P to 3 P , demonstrating that LFW is an excellent manufacturing technology with a wide range of possible processing conditions. As an elemental technology for blisks, LFW may potentially allow for even greater weight reductions by using hollow blade parts and more suitable materials for the disk and blades, and it is anticipated that LFW technology will continue to mature.

We will continue to pursue practical research to achieve even greater weight reductions in the future.



(Note) *1 : Inclination about the axis perpendicular to the short edge
*2 : Inclination about the axis perpendicular to the long edge

Fig. 11 Measurement of variation of LFW joint inclination

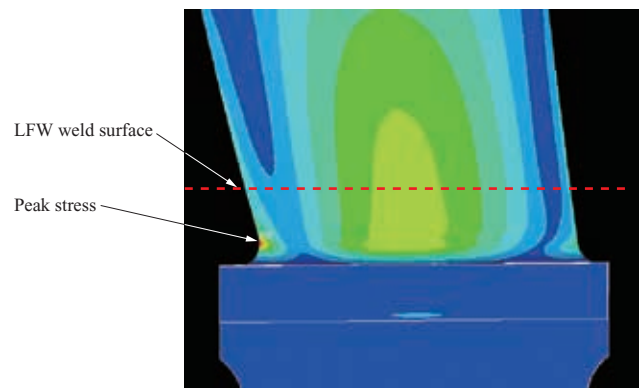


Fig. 12 Vibratory stress distribution of HCF test specimen

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