Finite Element Simulation of Ultrasound Propagating Through the Interface of Diffusion Bonded Dissimilar Nickel-Based Alloys

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Abstract. Powder metallurgy and cast nickel-based alloys are diffusion bonded together to make desired performance. Whereas, the ultrasonic inspection of defects within the bonding interface are difficult due to the great grain size difference between the two sides. A model-based research on the ultrasonic characterization of the diffusion bonded interface was presented. A 2D finite element model was developed based on Abaqus to describe the material, where the orientation of each grain was obtained by EBSD technique. The propagation of ultrasound in the sample was predicted and the reflection coefficient was calculated which was verified to the experimental ultrasonic response.

Introduction

Nickel-based superalloys are used to manufacture parts and assemblies of great importance in aeroengines, such as turbine blades and disks. However, the requirements of materials differ for disks from that for blades due to different working conditions. Normally, a gas turbine blade works at a temperature of 1000ºC–1200ºC, and requires high creep resistance and long-term strength. In comparison, a gas turbine disk works at a lower temperature of less than 800ºC, and requires high temperature strength and fatigue resistance. In most cases, cast nickel-based alloys are used for the manufacture of blades and powder metallurgical alloys for disks.

In order to integrate a disk with the surrounding blades, welded structure were applied, diffusion bonding in particular[1][2]. As a solid state welding technique, diffusion bonding is capable of providing perfect joint of nearly the same strength as parental materials, and ideal to join dissimilar materials. It is desirable to diffusion bond together nickel-based alloys of differing types. It is known that defects sometimes develop at the bond interface zone, which are often very high aspect ratio de-bond zones between the differing alloys with a size of up to hundreds of microns. In these circumstances, the defects are large compared to the PM alloy grains (~10µm), but small (or the same order size) relative to the adjacent, large-grained alloy (~150µm). It is highly desirable to be able to detect defects using ultrasonic techniques. However, due to the great grain size difference, the interface itself would be a reflector and give a background reflection, which cause difficulties in the interpretation and recognition of the ultrasonic indications.
To address these difficulties, a variety of models were developed to understand how the ultrasound propagates through an interface. Both frequency domain[3][4] and time domain[5][6] techniques were paid attention to by researchers worldwide. For a long time, distributed spring model[7][8] were used to describe the quality of the diffusion bonding and to predict the propagation of ultrasound through a bonding interface. However, due to the complication of the physical process, the application was limited by its over-simplification and inaccuracy.

Finite element method, as a numerical tool, is widely used to simulate elastic wave propagation, and found applications in a variety of sophisticated acoustic phenomena and problems such as air-coupled UT[9], laser UT and EMAT[10]. With the advent of increased computer power and greater availability of software these simulations have become more readily available and will provide improved insight into wave propagation problems. In the present work, a 2D finite element model of interface propagation of ultrasound was established based on Abaqus/Explicit. The crystals morphology and orientation were acquired in EBSD scans and used as an input in the model. The interface propagation was simulated and compared to the ultrasonic response for verification.

1. Theoretical background

For an elastic wave in an infinite homogeneous and purely anisotropic medium, the propagating behaviour is controlled by Navier-Cauchy equation, expressed in the tensor form as

$$\frac{\partial}{\partial x_j} \left(C_{ijkl} \frac{\partial u_k}{\partial x_l} \right) = \rho \frac{\partial^2 u_i}{\partial t^2} \tag{1}$$

where i, j, k and l are the summation/repetition subscripts and range from 1 to 3. $C_{ijkl}$ is the elastic constants of the solid and varies for different materials. $\rho$ denotes the density, $x_i$ the position in the ith direction and $u_i$ the local displacement in the point defined by $x_i$.

Consider the solution of a harmonic wave of frequency $\omega$, which is expressed as

$$u_i = A_i \exp[j(k_i x_i - \omega t)] \tag{2}$$

where $A_i$ is magnitude of the wave, j the imaginary unit, $k_i$ the wave number in the lth direction. Substituting Eq. (2) into Eq. (1) yields

$$(C_{ijkl}k_i k_j - \rho \omega^2 \delta_{ik})A_k = 0 \tag{3}$$

Further, define $n_i = k_i/k$ and introduce Christoffel tensor $\lambda_{ik} = C_{ijkl} n_l n_j$. We can get

$$(\lambda_{ik} - \rho c^2 \delta_{ik})A_k = 0 \tag{4}$$

where $c^2 = \omega^2/k^2$.

Eq. (4) is the typical eigenvalue problem and has three solutions at most. Each solution gives an eigenvalue and the corresponding eigenvector representing the phase velocity of the wave and its polarization direction, respectively.

Assume an elastic wave of the form Eq. (2) is propagating through an interface, as is shown in Fig. 1. It follows both Eq. (3) and the continuity condition, expressed as

$$\sigma^x_{ij} (0) = \sigma^\beta_{ij} (0) \tag{5}$$

$$u^x_j (0) = u^\beta_j (0) \tag{6}$$

where the superscripts $\alpha$ and $\beta$ denote the medium in which the stress or the displacement are measured. A direct deduction is that the $x_1$ and $x_2$ components of the wave vector for the reflecting and refracting waves remain the same as the incident one. By solving these equations, one can get the velocity, the polarization and the wave vector of the reflecting and transmission waves and make a best prediction of the propagation.
It is quite straightforward for a perfect interface. In a more general case where the interface is defective, a quasi-static spring model was introduced. The interface was considered as a series of distributed springs with varied stiffness $K$ which represents the bonding condition of the corresponding location, expressed as

$$\sigma_\alpha^j(0) - \sigma_\beta^j(0) = -\frac{m\omega^2}{2}[u_j^\alpha(0) + u_j^\beta(0)]$$ (7)

$$\frac{1}{2}[\sigma_\alpha^j(0) + \sigma_\beta^j(0)] = K_\beta[u_j^\alpha(0) - u_j^\beta(0)]$$ (8)

For a perfect interface, the stiffness $K$ tends to be infinite and the relations turn into Eq. (5) and Eq. (6). For a perfectly non-bonded interface, $K$ tends to be zero. More generally, the value of $K$ is within the range of zero to infinity.

2. Experimental procedures

The workflow chart is shown in Fig. 2. A sample were fabricated by diffusion bonding with a flawless interface. To obtain the crystal morphology and orientation information for the finite element model, the sample were subject to a cutting and grinding procedure followed by an EBSD analysis. The information acquired in the EBSD analysis was used as an input for the finite element modelling of the material. Since the EBSD procedure would inevitably destruct the sample, a thorough scan was performed by means of immersed ultrasound before the EBSD procedure. Finally, the simulation and experimental results were put together for a comparison.
2.1 Samples preparation

Two 50mm-in-diameter cylinders of different type of Ni based alloy were bonded together with Hot Isostatic Pressing (HIP) technique. And then a rectangle was cut from the bonded sample with a cross-section of 45mm x 45mm in dimension. One side is 64mm-in-thick fine-grained (~20μm) PM alloy and the other is 5mm-in-thick coarse-grained (~150μm) cast alloy. Several trials and metallography tests were performed before the final bonding to ensure the bonding condition of the sample.

On the coarse-grained side, a Φ1.2mm flat bottom hole was drilled to the bonding interface, as shown in Fig. 3.

Fig. 3 Diffusion bonding sample a) illustration of the sample structure and b) metallography of bonded interface
2.2 Ultrasonic characterization

The sample was thoroughly characterized with immersed ultrasonic testing before being cut for the EBSD scan. UTEX 340 was used as the pulser and receiver. A 10MHz probe with a focus of 400mm in water was used in the test. The water path was set so that the focus was located right on the interface. During the test, a C scan was performed with the probe translating in a plane paralleled to the bonding interface. The resolution was 0.1mm×0.1mm and the full waveform of every position was stored for the verification.

2.3 EBSD analysis

The sample mentioned in 2.1 was cut into a smaller one to fit in the EBSD chamber. A cut was made perpendicularly to the bonding interface through the center line of the sample. The region of interest is a 20mm×5mm area on the coarse-grained side, as shown in Fig.4.

Before EBSD detection, the samples were ground with 320, 600, 2000 grits silicon papers in sequence, followed by a polishing step for 30min. A Zeiss Auriga Cross Beam SEM facility was used for the EBSD analysis. Since the coverage of a single EBSD scan was limited, multiple scans were performed and the images were combined afterwards to generate a whole picture of the cross-section.

The EBSD scanning results are shown in Fig.5. The dimension is 20mm in width and 5mm in height. Each grain is segregated from a neighbouring one by the colour. The legend of the figure on the right hand side is also a colormap, where the red, green and blue components correspond to the three Euler’s angels of each grain. It is worth noting that the predrilled flat bottom hole with a colour of pure black was located right in the centre of the sample. With the help of this figure, one can easily extract the shape and orientation of each crystal of the coarse-grained alloy, which will be used as an input parameter for the finite element model later.

3 Finite element model

A 2D finite element model of the microstructure around the bonding interface was established based on the Abaqus/Explicit CPS4R. Since the fine-grained alloy has a grain size much
smaller than the wavelength of the ultrasound, it was treated as a whole with a uniformly
distributed isotropic elasticity. In comparison, the cast alloy has a grain size the same scale
as the wavelength, and was treated as multiple crystals with independent stiffness in each
crystal.

3.1 Mesh

Firstly, the whole sample was meshed into grids with uniformly distributed elements and
nodes. The mesh needs to be fine enough both in the spatial and temporal aspect to capture
the displacement changes accurately along the ultrasound path. Another reason for the finer
mesh was to give an adequate resolution for the crystal contour. In this case, the node-to-
ode distance was set to 0.02mm.

3.2 Elasticity

For a single Ni-Based alloy crystal, the elasticity is anisotropic and can be fully characterized
by a stiffness matrix. In local coordinates, this matrix is constant, written as

\[
C = \begin{bmatrix}
251 & 153 & 153 \\
153 & 251 & 153 \\
153 & 153 & 251 \\
137 & & \\
137 & & \\
137 & & 
\end{bmatrix}
\tag{9}
\]

Due to the varied orientation of each crystal, a rotation has to be made to the matrix
to fit into the global coordinates, expressed as

\[
C' = R_D C R_D^{-1}
\tag{10}
\]

where \(R_D\) denotes the rotation matrix, which is determined by angles between the local co-
ordinates and the global ones. These angles are also called the Euler’s angle and can be meas-
ured with the help of EBSD. In fact, we already obtained the Euler’s angles of each crystal
in the cross-section in the EBSD analysis in 2.3.

Though the elasticity of a single crystal is anisotropic, in a larger scale, the overall
behaviour of the material may sometimes be similar to an isotropic crystal, on conditions that
(a) the crystals are isometric and randomly oriented and (b) the average size of the crystals
is much smaller than the ultrasound wavelength. In these cases, the material can be simplified
ultrasonically as a single isotropic crystal.

In this work, one of the bonding material is PM alloy and very fine-grained comparing
to the wavelength. Therefore, the PM alloy side off the bonding interface was set as one
partition and the material properties were set isotropic with a Young’s moduli of 207GPa and
Poisson Ratio of 0.28.

The lower part below the bonding interface were segregated into small partitions ac-
cording to the morphology of each grain, which was obtained by the EBSD analysis. The
material properties of each grain were defined in the form of a global stiffness matrix which
is calculated from the local matrix and the Euler’s angles of each grain.

3.3 Boundary conditions

In this work, the displacement direction of the wave is mainly along the \(x_3\) axis and the com-
ponents along the other two axes are relatively small. Therefore, it is reasonable to assume
the outer surface of the sample can only transfer vertical displacement. On the basis of this
assumption, points on the two sides were set so that the displacement in the \(x_1\) direction are
always zero. Besides, the far end of the sample was set as a free surface.
3.4 Ultrasonic wave loading

A Hanning modulated wave was used in the model as the source with the sampling rate of 250MHz, the central frequency of 10MHz, the bandwidth of 0.6 and the frequency resolution of 0.5MHz. Out of the above parameters, a time-varying stress was generated and imposed on the fine-grained side of the sample surface.

4 Simulation and Verification

Based on the model, the ultrasound propagation process was simulated, and the stress variation through time can be acquired, as shown in Fig. 6.

It can be seen from the figure that the wave propagated smoothly in the PM alloy. Though most of the energy transmitted through the interface, a small part of it was reflected when it hit the interface. In comparison, the artificial defects gave an extremely high reflection due to huge acoustic impedance difference between the two side of the interface.

Out of the simulation results, some useful information can be calculated, such as the local reflection coefficient. If we focus on a plane (which is a line in 2D) that is a few microns away above the interface, the displacement of every single point is available for every time point. Therefore, for each point we can get (a) the displacement when the wave propagates directly through it and (b) the displacement when the wave is reflected by the interface and propagate through it again. By simple dividing, the reflection coefficient of every point is calculated.

To verify the simulation results, we compared the calculated reflection coefficient with the C-scan data obtained in 2.2 and found the two coincide qualitatively, as shown in Fig.7.
Fig. 7 Calculated reflection coefficient and the interfacial response

The reflection coefficient of a Φ1.2mm flat bottom hole was around 80% at the peak, while the interface gave a reflection coefficient less than 15% in average. Therefore, in an ideal world, the reflection of an imperfect bonding interface will be within the range of 15% to 80%. Empirically a 6dB SNR has to be maintained for clear recognition, so the detectable disbond is 30% and above.

In the experimental case, what was measured was not the reflection coefficient but the response instead which was dominated by the reflection coefficient, but affected by more factors such as the attenuation of the ultrasound, the focussing and defocussing of the beam. Therefore, the difference between the reflection from the FBH and that from the interface was small compared to the simulation. Consequently, the sensitivity that can be achieved is reduced.

5 Conclusion

In the present work, a 2D finite element model was developed based on the Abaqus/Explicit architect to investigate the propagation of ultrasound through the diffusion bonding interface of dissimilar Ni based alloys, taking into account the anisotropic elasticity of the coarse-grained alloy. The real morphology and orientation of each crystal on the cross-section of the sample were acquired by EBSD analysis and used as an input parameter in the model. The vertical displacement field was simulated for a series of time points which illustrated the propagating process of the ultrasound. The local reflection coefficient was extracted and calculated for the bonding interface with and without a flat bottom hole, and was compared to the ultrasonic response for verification. In an ideal world, a disbond with 30% reflection is detectable, but a reduced sensitivity is expected for real inspections.

Reference