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School of Materials Engineering

Understanding the Relationship Between Surface Morphology and Mechanical Strength of Titanium (Ti) Foil Laser Bonded to Sapphire Wafers

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Medtronic has developed a mechanical peel test used to measure the strength of titanium (Ti) bonded to sapphire wafers via laser processing. The peel test is employed to measure and trend the consistency of the laser bonding process. Medtronic has understood that many factors can affect the peel strength of the bonds, including laser-related factors such as power, overlap, focal plane location, and optics-related defects. However, variations within the titanium foil have also been shown to affect the resulting peel strength. The intention of this project will be to fundamentally characterize the relationship between foil surface morphology and the resulting peel strength of the laser bonded interface between the titanium foil and sapphire.

This work is sponsored by Medtronic, Phoenix, AZ
Medtronic

Background

Medtronic's LINQ II heart monitor is an implantable cardiac monitor (ICM), which is a small device placed in the muscle of a patient's chest to record the electrical activity of their heart. The electrical activity can indicate rare or irregular heartbeats, which could cause a wide variety of symptoms. These heart monitors allow doctors and other medical professionals to easily diagnose long-term heart problems which might not be detected by a short test.

In 2015, Medtronic started testing on laser bonding titanium foil to sapphire wafers, since both materials are biocompatible and durable and therefore are good options for long-lasting implants. The electronics of the heart monitor are built on the sapphire wafer, while the majority of the heart monitor is the titanium casing of the battery. The wafer is then laser bonded to the titanium battery in order to form a hermetic seal. A high-quality hermetic seal is essential, as the airtight, impermeable barrier prevents cross-contamination between bodily fluids and the electronics inside the heart monitor.

Laser bonding is a manufacturing process which uses rapid, high precision laser pulses to join or seal two materials together. The focused laser beams create strong bonds between the materials. The process is used for manufacturing specialized materials and is commonly used in almost all electronics manufacturing. Surface morphology on materials being laser bonded can have a significant impact on the quality of the laser bond. Surface roughness or waviness can alter the interactions between the laser and the surface. If the wavelength of the light is similar to the dimensions of roughness, more light can be reflected off the surface, which decreases the effective laser power. Roughness can also create gaps between the foil and substrate. If the gap between the two is too large, the melt pool formed by the laser cannot span the gap and will result in a weak bond. Therefore, poorer surface quality often corresponds to a poorer bond quality and peel strength.

Experimental Design

As the goal of this study is to correlate the surface morphology of the titanium foil to the peel strength of the titanium-sapphire bond, it was essential to collect a diverse set of data that accurately describes the surface morphology of the foil samples. Medtronic provided us with six distinct batches of foil, with each batch containing six samples. Each batch of foil has a different peel strength, as shown in the table below, with individual samples providing some degree of variability. In order to analyze the general surface morphology of the thirty-six total samples, a combination of optical microscopy, confocal microscopy, and atomic force microscopy (AFM).

The titanium foil sample were first analyzed using an Olympus BX41M Metallurgical Microscope and a Keyence VHX-7000 Confocal Microscope. Optical and confocal imaging focused on imaging the overall striation patterns on several magnification levels, while confocal imaging also focused on imaging any visible defects and contamination. Overall, nearly 300 images of the samples were taken in order to gain a clearer picture of the visible surface details. A custom MATLAB script was then used to measure the aspect ratio of the striations and surface features. By converting the images to black and white and measuring the consecutive numbers of black pixels, the script determined the vertical and horizontal feature lengths, as well as the number of features present. This allowed for any anisotropy in the features of an image to be identified and quantified for future comparison.

To complement optical and confocal microscopy, the titanium foil samples were further analyzed using a Bruker Dimension Icon AFM to obtain high-resolution surface topography at the micro- and nanoscale. AFM imaging focused on features such as peak-valley amplitude, waviness, and fine-scale roughness that are not fully resolved using optical and confocal method. Multiple regions on each sample were scanned to capture variability in surface morphology. The resulting height maps were used to extract both qualitative and quantitative parameters and will be combined with optical and confocal microscopy to better correlate surface characteristics with peel strength performance. This data will be used to find correlations between the striation directions and heights and the peel strength of the foil when bonded to sapphire wafers.

Batch Number	Medtronic Peel Strength
0012878100T09	Known Low
0012878100T08	Suspected Low
0012889982T04	Suspected Low
0013078074T01	Suspected Good
0013101030T01	Suspected Good
0013045221T10	Known Good

Key Results

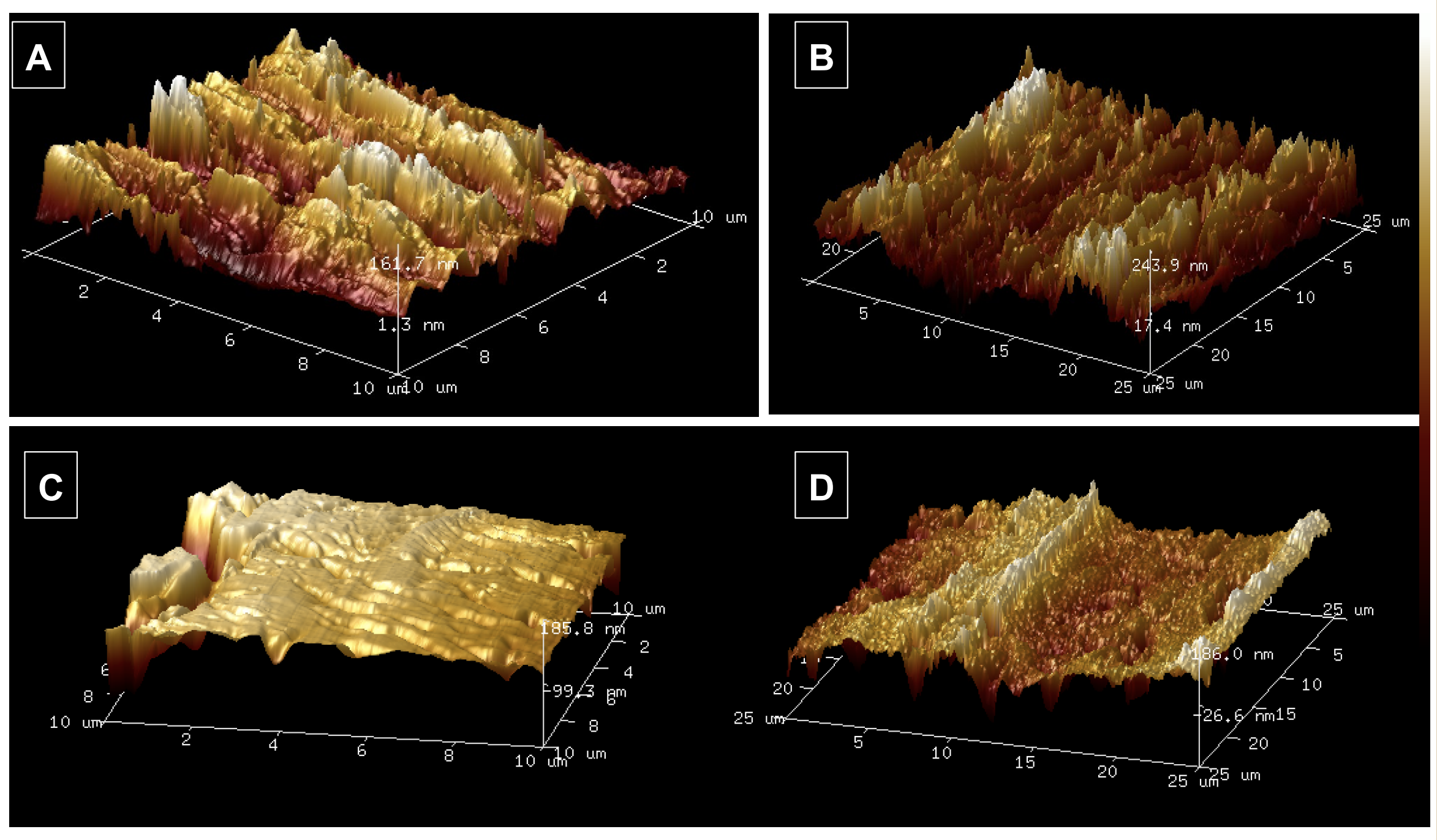

Fig 1. AFM 3D surface topography of Ti foil samples. **Samples A (100T09)** and **B (982T04)** exhibit higher surface roughness. In contrast, **samples C (221T10)** and **D (221T10)** show smoother, more uniform surface.

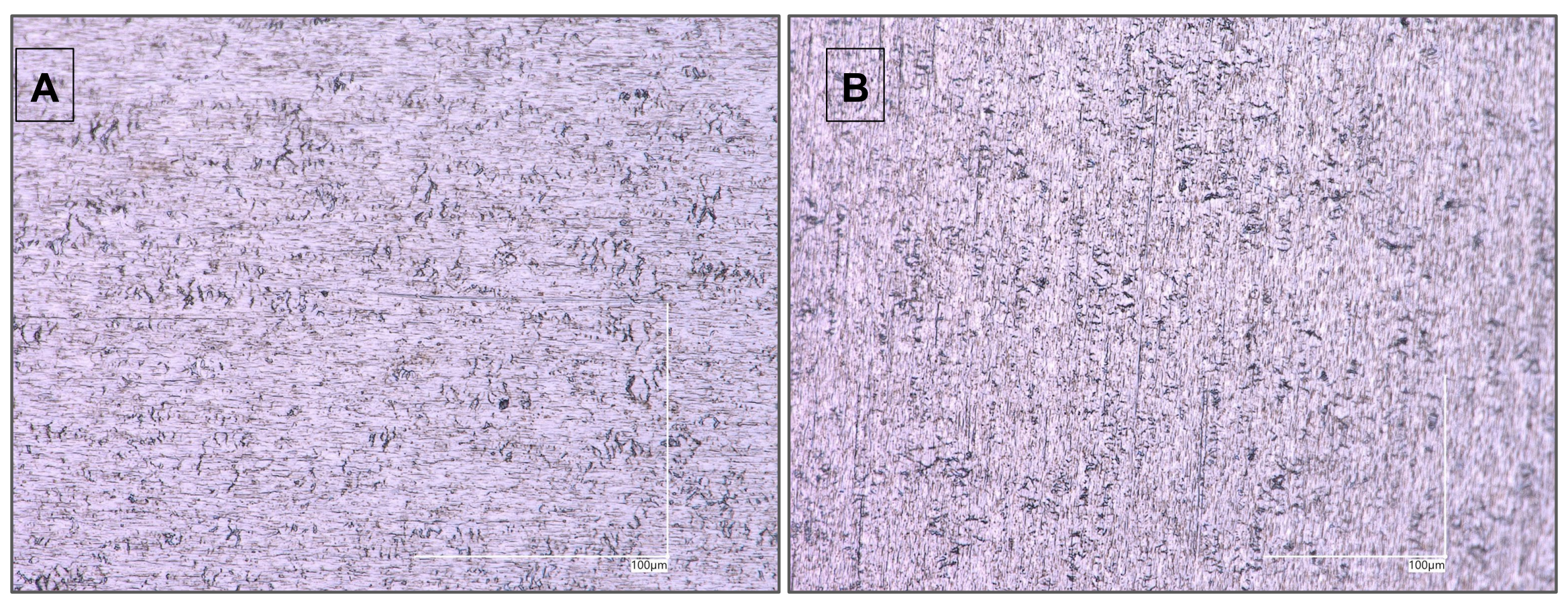

Fig 2. Confocal images of **Sample A (100T09)** and **Sample B (100T08)**, with striation orientation parallel and perpendicular to the flat, respectively.

Table 1. Surface roughness parameters

Batch Number	Ra (nm)	Rq (nm)	Rmax (nm)
0012889982T04	45.7	59.8	646
0013045221T10	39.8	53.3	525

Table 1 shows the measured surface roughness parameters for (Ra, Rq, and Rmax) for selected Ti foil batches, providing quantitative comparison of surface morphology. The results indicate noticeable variation between batches, with **982T04** exhibiting higher roughness compared to **221T10**. These differences reflect greater peak-valley height and surface irregularity which are characteristic of more pronounced waviness and non-uniform deformation. In contrast, lower roughness values correspond to smoother and more uniform surfaces, which are expected to enable more consistent contact during laser bonding. These findings support the role of surface morphology as a key factor influencing bonding performance and provide a basis for distinguishing between higher and lower quality of foil batches

Table 2. Aspect ratio and striation direction for titanium foil batches

Batch Number	Avg. Aspect Ratio	Striation Direction
0012878100T09	0.596	Horizontal
0012878100T08	1.084	Vertical
0012889982T04	0.743	Horizontal
0013078074T01	0.811	Horizontal
0013101030T01	0.847	Horizontal
0013045221T10	0.737	Horizontal

The table above summarizes the average aspect ratios of the six batches of titanium foil as given by the MATLAB script. The aspect ratio serves as a quantitative indicator of the directionality of the striations, as an alternative to a purely visual approach. An aspect ratio of of greater than one indicates that the striations are longer vertically than horizontally, while an aspect ratio of less than one indicates that the striation is longer horizontally than vertically. As shown in the data, five of the six batches have an aspect ratio of less than one, indicating that the striations are oriented in the horizontal direction. Half of the samples have an aspect ratio between 0.750 and 0.595, showing that on average these batches tend to have surface characteristics that are 33.3-67.8% longer in the horizontal direction, indicating a relatively strong anisotropy. The variety of aspect ratios show that the anisotropy present in the foils varies between batches but is always present. All of the striation directions can be confirmed visually in the foils, aligning with the quantitative results shown above in the table and increasing confidence in the use of aspect ratio as a reliable metric.

Discussion

Confocal and Optical Microscopy:

Based on analysis of the optical and confocal images, it was concluded that there is no direct relationship present between the striation orientation and peel strength within the dataset collected. Although striation orientation was expected to have some correlation with bonding performance, the results show that striation orientation is not a reliable predictor of bond performance. Five of the six batches have striations aligned in the horizontal direction, and yet those same five batches exhibit a variety of peel strength values as reported by Medtronic. The final foil batch has striations oriented in the vertical direction instead of horizontal. While this batch of foil is suspected to result in poor peel test data, its status as the only batch with vertical striations likely means that the poor peel test data is likely due to another cause and is not caused by striation anisotropy.

This conclusion is further reinforced when examining key batches: 100T09, which recorded low peel strength, and 221T10, which recorded high peel strength. Despite their notable difference in bonding performance, both batches had horizontal striations and aspect ratios well below one. If striation directionality had a strong influence over peel strength, a more significant difference in aspect ratio and striation direction would be expected (similar to what is seen in Fig. 2). Instead, the similarity in striation orientation reinforces the idea that directionality alone cannot influence bond strength, and that other aspects of surface features, such as the height of striations, could have a more significant impact on the peel strength of the foil.

Atomic Force Microscopy (AFM):

AFM was critical in determining the correlation between surface waviness and foil quality. This technique measures the extreme peaks and valleys of a surface, allowing visualization of the surface morphology on the nanometer scale. Foils with a greater height difference between extreme peaks and valleys correlated to lower quality foils, as observed in batches including 100T08 and 100T09. This is to be expected, as rastering is more inefficient across extreme peaks and valleys, resulting in uneven melt pools that diminish foil quality. Considering that these batches had vastly different striation orientations, as seen in Fig. 2, but their surfaces displayed similar waviness morphology, it is clear that surface waviness contributes to poor foil quality and bond strength.

Overall, the AFM results support the conclusion that both the magnitude and uniformity of surface waviness are key indicators of foil quality. Samples exhibiting larger peak-valley differences and irregular surface features correspond to poorer quality foils (eg. Fig. 1A and 1B), while smoother more uniform surfaces are associated with improved bonding potential. These findings suggest that controlling waviness characteristics is critical for achieving consistent laser bonding performance, and that AFM-driven metrics can serve as effective predictors of peel strength variability.

Recommendations for Future Work

Based on the combined analysis of the data collected from optical, confocal, and AFM, it is reccomended that Medtronic focus on minimum surface roughness thresholds over measuring striation orientations. The results clearly indicate that striation direction does not have a meaningful correlation with peel strength. However, data collected using AFM shows that the surface roughness from striations, independent of direction, can impact the peel strength, and should therefore be the focus of pre-manufacturing tests.

To build on the findings of this study, further research should be done on individual defects and contaminations. Scanning electron microscopy (SEM) and X-Ray Diffraction (XRD) could be used to examine microstructural defects and crystallographic characteristics of the titanium foils.

Acknowledgements & References

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