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Palardy, G.; Fernandez Villegas, I.

Publication date

2016

Document Version

Final published version

Published in

Proceedings of the American Society for Composites - 31st Technical Conference, ASC 2016

Citation (APA)

Palardy, G., & Fernandez Villegas, I. (2016). Smart ultrasonic welding of thermoplastic composites. In B. D. Davidson, M. W. Czabaj, & J. G. Ratcliffe (Eds.), *Proceedings of the American Society for Composites - 31st Technical Conference, ASC 2016* DEStech Publications Inc..

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Smart Ultrasonic Welding of Thermoplastic Composites

G. PALARDY and I. F. VILLEGAS

ABSTRACT

This paper presents an overview of the latest research on ultrasonic welding of composites performed at the Delft University of Technology. Firstly, we showed that for thermoplastic composites, a simple flat energy director shape, made of a loose film of neat resin, can be used to produce welds of high quality. Furthermore, for single lap shear coupons, it was shown that the use of a microprocessor-controlled welder allows for in-situ monitoring through power and sonotrode displacement data. As a result, a smart ultrasonic welding procedure was designed in which the feedback from the ultrasonic welder was used to define the processing parameters that yield optimum weld quality, significantly decreasing development times. Based on the knowledge developed at a lab-scale level, a welding strategy was developed to demonstrate the assembly of small and medium-sized components. Experimental comparison between ultrasonically spot-welded and mechanically fastened joints into double-lap shear and pull-through configurations further outlined the potential application of this technology, as well as its limitations. While ultrasonic welding is an efficient technique to join thermoplastic composites components, another potential application was shown to be the welding of thermoplastic and thermoset composites, enabled through the very short heating times in the ultrasonic welding process. This opens up new possibilities for ultrasonic welding where optimum design and manufacturing of aircraft parts call for the assembly of dissimilar materials, and could lead to significant costs and weight reduction as compared to mechanical fastening.

INTRODUCTION

Owing to the ability of thermoplastic polymers to be melted when heated above a specific temperature and recover their initial properties after cooling down, thermoplastic composites (TPCs) can be welded through fusion bonding [1]. This assembly method is an attractive alternative to joining techniques traditionally applied to thermoset composites (TSCs), such as mechanical fastening and adhesive bonding. Ultrasonic welding (USW), classified as a type of friction welding, is a promising method because of its ultra-short cycle times (less than a few seconds), absence of foreign materials at the interface, and potential for process monitoring and automation.

While USW has been used in the plastics industry for several decades, research into industrialization for structural joining of TPC components is limited. Some investigation into process monitoring through dynamic mechanical impedance, as well as sequential welding of large overlaps, has been carried out, but there was no follow-up into current applicability [2, 3]. Another important aspect of USW is the use of energy directors (EDs) at the welding interface. They are resin asperities responsible for local heat generation and are typically shaped like triangular ridges, directly molded on the adherends' surface. Comparison between various shapes of energy directors has been mostly performed through finite element analysis [4-7], but did not take into consideration the manufacturing impracticalities of these protrusions encountered with thermoplastic composites.

In order to reach the appropriate readiness level and develop robust welding procedures for USW of TPCs, a deeper understanding of several aspects of this technology still needs to be achieved. This paper presents an overview of the latest research performed at the Delft University of Technology and as such, four main topics are expanded upon: 1) energy director geometry, 2) in-situ process monitoring and optimal processing conditions with respect to weld quality, 3) welding of dissimilar materials, and 4) sequential welding for up-scaling.

ULTRASONIC WELDING PROCESS

In the research performed at the Delft University of Technology, a Rinco microprocessor-controlled ultrasonic welder was used, as shown in Figure 1. The machine transversally applies pressure and high frequency (20kHz), low amplitude vibrations on the top surface of the upper adherend through a sonotrode. The dimensions and shape of the latter were selected based on the size of the parts to join. Following the vibration phase, a solidification phase, during which the weld is allowed to cool down under pressure, is required for adequate consolidation. The duration of the vibration can be controlled with time, energy or vertical displacement of the sonotrode (also referred to as "travel"). After each weld, the USW machine provides the following outputs: dissipated power and sonotrode displacement curves, as well as vibration time, energy and maximum power.

Different custom-made clamping setups were designed and manufactured based on the type of components to be welded. An example of such a setup for single lap shear specimens is seen in Figure 1.

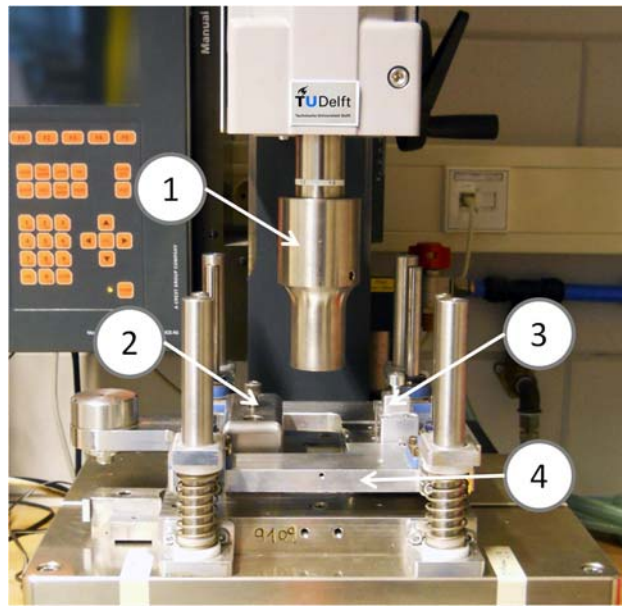


Figure 1: Example of one of the welding setups used to carry out experiments with single lap shear samples. 1: sonotrode, 2: clamp for the lower sample, 3: clamp for the upper sample, and 4: sliding platform.

RECENT DEVELOPMENTS

Energy Directors

Traditionally, in the plastics industry, energy directors are directly molded on the surfaces to be joined and are shaped like triangular, semi-circular or rectangular protrusions [4]. They heat up preferentially as a result of higher cyclic strains and concentrate heat generation at the interface through interfacial and viscoelastic friction [8]. However, for thermoplastic composites, this requires an additional manufacturing step and therefore, there was a need to find a simpler, alternative solution.

As such, the options depicted in Figure 2 were considered: four triangular energy directors molded on the surface of the bottom sample (4TMED) and a simple, flat energy director (FED), made of a thin polymer layer [9]. The main objective of that study was to assess whether the simplicity offered by the flat EDs hindered the welding process in any way. Figure 3 compares the average running load (R Load), vibration time (US time) and energy for flat and triangular EDs. The results demonstrate there are no significant differences between all outputs. This confirmed that using FEDs in those conditions (materials and welding parameters) did not have any negative influence on the welding process and that this solution can be considered for further applications.

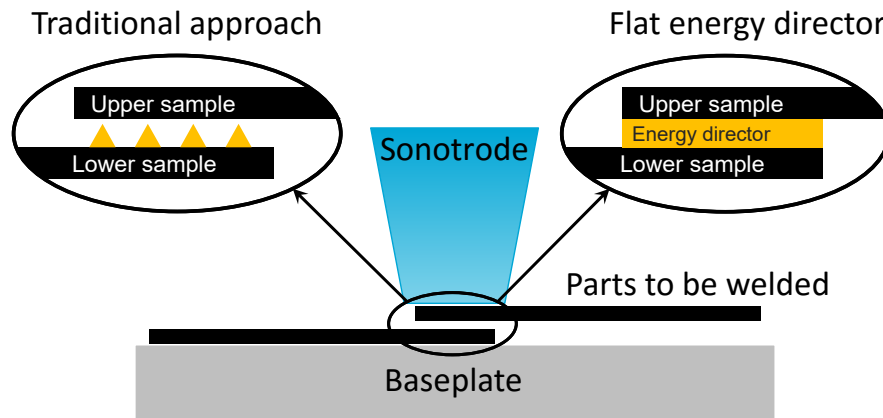


Figure 2: Ultrasonic welding process depicting triangular molded energy directors (4TMED) and a flat energy director (FED). Dimensions are not to scale.

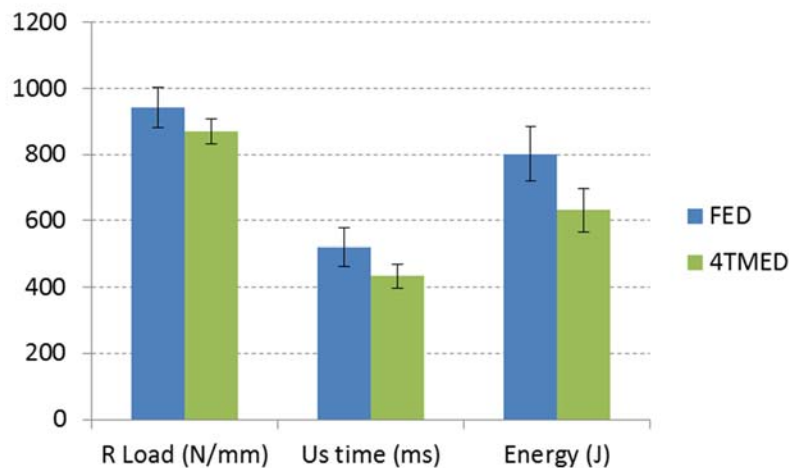


Figure 3: Running load (R Load), welding time (US time) and energy for carbon fiber/polyphenylene sulfide (CF/PPS) samples welded using flat energy directors (FED) and triangular energy directors (4TMED) (500 N welding force and 86.2 μm vibration amplitude).

In-Situ Monitoring and Optimum Processing Conditions

To further deepen knowledge of USW of TPCs, it is necessary to properly monitor the process to quickly identify the optimum welding parameters when using flat energy directors. For single lap shear coupons, it was shown that the use of a microprocessor-controlled welder allows for in-situ monitoring through power and sonotrode displacement data [10, 11]. Fractography and cross-sectional analyses revealed that this feedback could be linked to physical changes occurring at the welding interface and hence to the quality of the welded joints. Based on the power and displacement curves provided by the welder, the process can be divided into five steps, as shown in Figure 4:

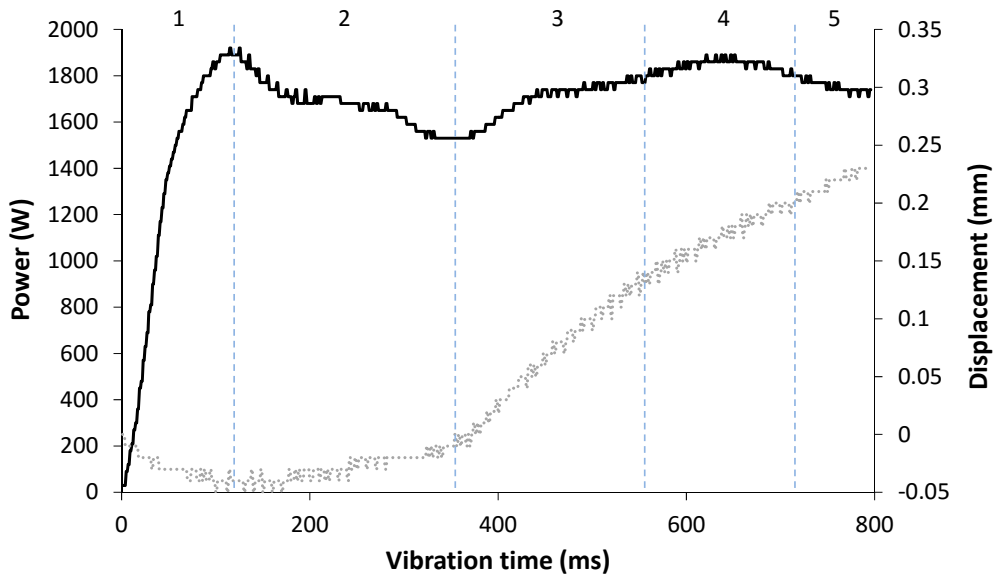


Figure 4: Typical power/displacement curves during the vibration phase of the USW process for CF/polyetherimide (PEI) (500 N welding force and 86.2 μm amplitude). Positive values in the displacement indicate downward displacement of the sonotrode. (Adapted from [11] and [12].)

After melting of the energy director through nucleation and growth of random hot spots in stage 2, the onset of the squeeze flow of the ED can be clearly seen by the downward displacement of the sonotrode in stage 3. The corresponding increase in power comes from the increased mechanical impedance of the interface when all melt fronts (hot spots) meet. Stage 4 is represented by a power plateau, during which the ED continues to flow and the upper layers of the composite samples start melting. In the last stage, associated with a power decline, the ED is completely squeezed out of the overlap, along with composite matrix and fibers.

To confirm the location of highest lap shear strength (LSS), specimens were welded at different travel values (displacement of the sonotrode expressed as a % value of the initial thickness of the ED) and under different welding conditions. An example is shown in Figure 5 in which maximum LSS is achieved around 40% travel. It was observed that there is a consistent relationship between LSS and the welding stages as defined in Figure 4. The strength of the joints increases during stage 3 and stage 4, and reaches a maximum towards the end of stage 4, then decreases in the last phase. Therefore, as highest weld strength is obtained within stage 4 of the process, it constitutes a target for optimum welding conditions, which has to be identified for each welding force and amplitude combination, based on the power and displacement curves.

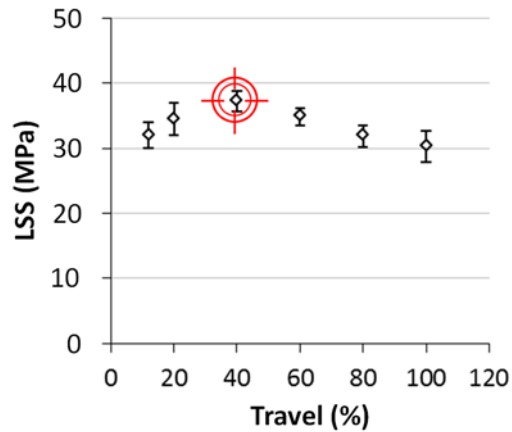


Figure 5: Lap shear strength of CF/PEI. Travel is expressed with respect to the initial thickness of the ED (300 N welding force and 86.2 μm vibration amplitude). The target sign indicates the location of maximum weld strength achieved within stage 4 of the welding process. (Adapted from [10].)

Welding of Thermoset Composites

While USW is an efficient technique to join TPC to TPC components, another foreseen application, owing to the fast processing time, is welding of dissimilar materials, such as thermoplastic to thermoset composites. A fully experimental study focused on prevention of thermal degradation during welding of CF/PEEK (poly ether ether ketone) to CF/epoxy composites through very short heating times demonstrated such a possibility [13]. Two types of welding were considered: 1) direct welding in which a flat PEEK energy director was placed between the CF/PEEK and CF/epoxy adherends, and 2) indirect welding in which a PEEK coating layer was co-cured onto the CF/epoxy substrate, in addition to the use of a flat PEEK ED. Two different heating times, 460 ms and 830 ms, were selected and controlled through the welding force and vibration amplitude.

CF/epoxy fracture surfaces from direct welding at both heating times were non-uniform, showing smooth resin-rich areas, as well as visibly damaged areas (Figure 6 (a)). For indirect welding, fracture surfaces with no visual signs of damage and a smooth resin-rich appearance were obtained in the short-heating-time case only (Figure 6 (b)). Fourier transform infrared (FTIR) spectroscopy revealed that thermal degradation of the CF/epoxy adherend was effectively prevented in this case, as a result of the PEEK coating layer acting as a heat shield. Further research into the improvement of adhesion between the thermoplastic coating and the epoxy substrate could lead to failure into the TPC substrate and enhanced weld strength.

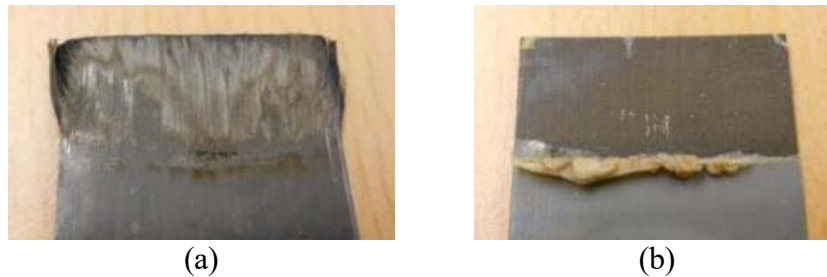


Figure 6: Representative CF/epoxy fracture surfaces after (a) direct welding under long-heating-time conditions, and (b) indirect welding under short-heating-time conditions.

(Adapted from [13].)

ONGOING DEVELOPMENTS

Sequential Ultrasonic Welding

To further advance the technological readiness of USW for TPCs in the aerospace industry, the development of welding strategies for small and medium-sized parts is required. A first step into this direction was taken within the scope of the Clean Sky Joint Technology Initiative (JTI), a public – private partnership between the European Commission and the aeronautical industry, working on reducing the environmental impact of aviation. The Faculty of Aerospace Engineering of Delft University of Technology coordinated the activities for the design and manufacturing of the F1 Eco-Design demonstrator, a thermoplastic composite airframe panel (Figure 7 (a)) [14]. Based on the knowledge acquired through in-situ monitoring and optimum welding parameters at a lab-scale level with flat energy directors, two pairs of components were welded: CF/PEEK hinges to CF/PEEK structural C-frames using a single spot-welded joint (Figure 7 (b)), and CF/polyether ketone ketone (PEKK) clips to CF/PEEK C-frames using sequential ultrasonic spot-welding (Figure 7 (c)). The potential of USW for up-scaling was clearly proven, but further research and development is required before it can be industrially applied.

Furthermore, another point of interest for up-scaling of the USW process is to provide an objective comparison with existing joining technologies, such as mechanical fastening. As a first step, an investigation of the in-plane and out-of-plane mechanical behavior between ultrasonically spot welded and riveted joints was carried out [15]. Double-lap shear tests performed on single joint configurations revealed that spot welds possess a comparable ultimate failure load with a 100% increase in the joint stiffness when compared to rivets (Figure 8 (a)). Examination of the damaged area with C-scan showed that it was significantly more severe in the case of mechanical fasteners, with delaminations through the laminates' thickness and propagation from the bolted hole (Figure 8 (b)). The mechanical performance of welded joints under peel (pull-through tests) was inferior to mechanical fasteners, but similar findings regarding the damaged area were observed. This highlights the potential of welded joints to be re-used or repaired after failure, whereas components

with bolted holes likely require a more complex replacement procedure. Future research will be aimed at the mechanical performance of multi-spot welded joints.

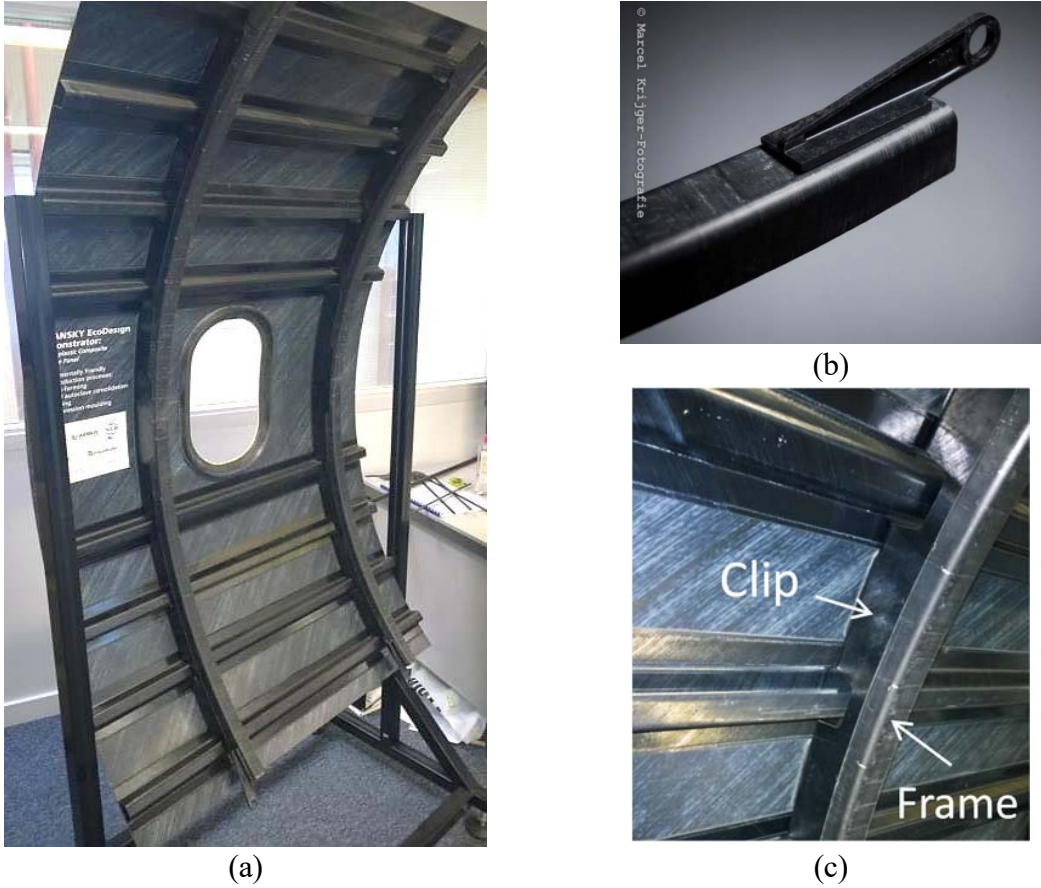


Figure 7: (a) F1 Eco-Design thermoplastic composite airframe panel demonstrator, (b) CF/PEEK hinge welded to CF/PEEK structural C-frame, and (c) CF/PEEK clip sequentially welded to CF/PEEK C-frame.

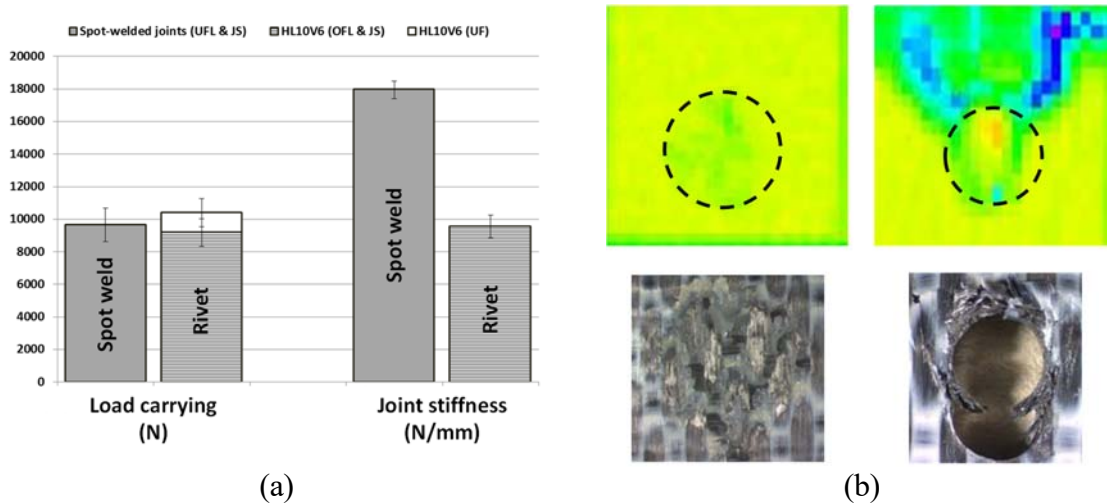


Figure 8: (a) Comparison of mechanical performance between spot welded and mechanically fastened joints in double lap-shear tests (UFL: ultimate failure load, JS: joint stiffness, OFL: onset of failure load), and (b) Comparison of the damaged area of spot welded and mechanically fastened joints after DLS tests (the black circles indicate the welded area and bolted hole). (Adapted from [15].)

CONCLUSIONS

This paper presented an overview of the most recent and ongoing developments in ultrasonic welding of thermoplastic composites at the Delft University of Technology. The main highlights were as follows:

- The use of simplified flat energy directors does not have a negative impact on the welding process and leads to welds of similar quality when compared to the traditional triangular EDs.
- In-situ process monitoring is possible based on the power and displacement curves provided by the welding machine and allows to quickly define optimum processing parameters. Maximum weld strength can be consistently obtained when controlling the process using the displacement of the sonotrode in stage 4 of the power curve.
- Welding of thermoset to thermoplastic composites can be achieved with ultra-fast welding times, well below 1 second, to effectively prevent the occurrence of thermal degradation in the thermoset adherends.
- Up-scaling of the USW process through sequential welding has been first demonstrated within the scope of a thermoplastic composite airframe panel. Experimental comparison between spot-welded and mechanically fastened joints into double-lap shear and pull-through configurations further outlined the potential application of this technology for re-usability and reparability.

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