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Studies on thermo-elastic heating of horns used in ultrasonic plastic welding

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ABSTRACT

Ultrasonic welding horn is half wavelength section or tool used to focus the ultrasonic vibrations to the components being welded. The horn is designed in such a way that it maximizes the amplitude of the sound wave passing through it. The ends of the horn represent the displacement anti-nodes and the center the 'node' of the wave. As the horns perform 20,000 cycles of expansion and contraction per second, they are highly stressed at the nodes and are heated owing to thermo-elastic effects. Considerable temperature rise may be observed in the horn, at the nodal region when working at high amplitudes indicating high stress levels leading to failure of horns due to cyclic loading. The limits for amplitude must therefore be evaluated for the safe working of the horn. Horns made of different materials have different thermo-elastic behaviors and hence different temperatures at the nodes and antinodes. This temperature field can be used as a control mechanism for setting the amplitude/weld parameters. Safe stress levels can be predicted using modal and harmonic analyses followed by a stress analysis to study the effect of cyclic loads. These are achieved using 'Ansys'. The maximum amplitude level obtained from the stress analysis is used as input for 'Comsol' to predict the temperature field. The actual temperature developed in the horn during operation is measured using infrared camera and compared with the simulated temperature. From experiments, it is observed that horn made of titanium had the lowest temperature rise at the critical region and can be expected to operate at amplitudes up to 77 μm without suffering failure due to cyclic loading. The method of predicting thermo-elastic stresses and temperature may be adopted by the industry for operating the horn within the safe stress limits thereby extending the life of the horn.

1. Introduction

Ultrasonic welding is an industrial technique whereby high-frequency ultrasonic acoustic vibrations are locally applied to work pieces being held together under pressure to create a solid-state weld. It is commonly used for plastics, and especially for joining dissimilar materials. It offers advantages in speed, economy and efficiency and is frequently chosen when parts are too complex or expensive to be molded in one piece. Weld times of less than one second are typical. However, it must be noted that the molded part and the process must be precisely tailored to each other, since the shape of the part to be welded influences the welding process.

Ultrasonic horns are tuned components designed to vibrate in a longitudinal mode at ultrasonic frequencies. Reliable performance of such horns is normally decided by the uniformity of amplitude of vibration at the working surface and the stresses developed during loading conditions. A horn designer must pay particular attention to design a tool that will produce the desired amplitude without fracture of the horn. A horn is usually a half wavelength metal component or tool designed to resonate at 20 kHz frequency (machine frequency). The shape of the horn determines the gain or magnification in amplitude. The cross section of horn is modified to provide an output shape as desired, producing either high amplitude-low energy (high gain) wave or low amplitude-high energy wave (low gain). Motion or vibration is produced by expansion and compression of the horn material. Mechanical vibration produced by the converter is axial in direction and the total movement of one complete cycle is in the range of 20 μm. Fig. 1 shows the schematic diagram of the amplitude transformation that is achieved from the converter to the horn end.

Vibrating horns are therefore stressed and for any given horn shape, the stress is proportional to the amplitude of vibration, therefore imposing a limit on the amplitude of vibration that a horn may be subjected to. When the horns are driven at high amplitudes, the chances of failure are high. Therefore, horns are made of materials which are strong, have good acoustical properties and resistance to failure due to cyclic loading. Titanium

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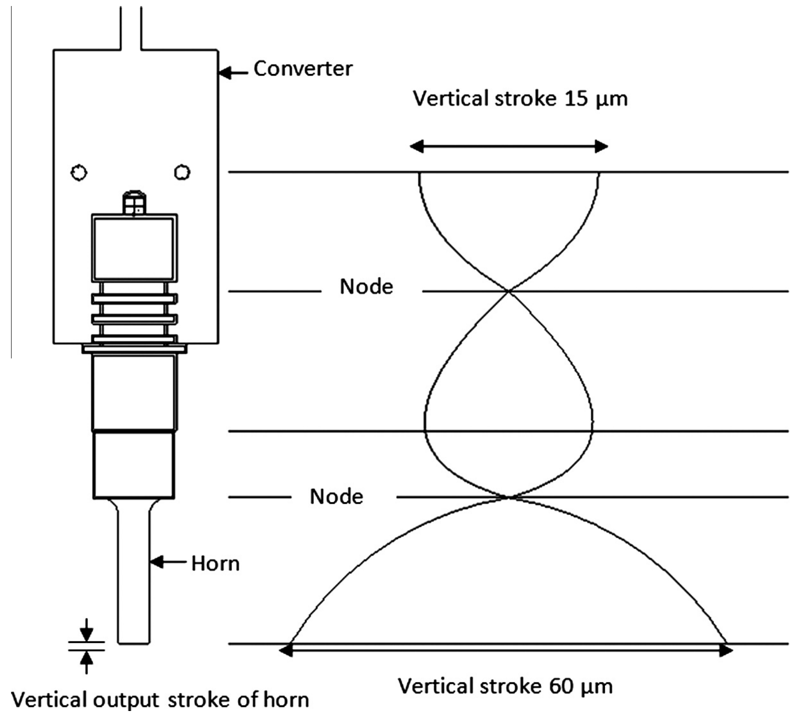

Fig. 1. Amplitude transformation from converter to horn end.

has the best acoustical properties of all high strength metallic materials and is the ideal material for fabricating horns. But its high cost is justified only when it is used for fabricating highly stressed horns like slotted horns and horns intended for mass production. Aluminum alloy has excellent acoustical properties and low density which is desirable but because of its low strength and hardness, it is subjected to wear and fracture when used in highly stressed designs. Monel metal is a high strength alloy but with acoustic properties inferior to that of titanium. Stainless steels offer many good characteristics as materials for ultrasonic horns. They exhibit high strength, stiffness, and excellent wear and corrosion resistance. They can also be used over a wide range of temperatures. The only limitation is their weight. Horns made of stainless steels are nearly three times denser than aluminum and approximately twice the weight of titanium horn. The poor acoustical properties of steel limit their use to low amplitude horns. Recently, Tantalum has also been used for the purpose of ultrasonic horn. Though it has very good acoustical properties, it is very expensive ($2000 for a single unit for a 20 kHz machine) and therefore not preferred by the industry, Ensminger and Stulen [1].

From literature review it is noted that research is carried out to understand the dynamics of the horn both analytically as well as by finite element methods. Optimization studies for design of horn were carried out by Graham et al. [2], Nad [3], and Wang et al. [4] using computational modeling as well as experiments. The exponential horn profile in longitudinal and torsional composite modes was studied by Lin [5]. A variety of novel horn designs was presented by Sherrit et al. [6] which could overcome some of the limitations of conventional designs. In a study, Gourley and Rushton [7] discussed the method of analyzing horn performance using finite element analysis. The horn integrity and assembly performance was analyzed using finite element analysis. Amin et al. [8] established a computer-aided design procedure for determining the horn profile based on finite element analysis. Design of Bar and Spool horns for producing uniform amplitude at the horn face was studied by Kim et al. [9].

Thermo-elastic heating is a phenomenon often used to study the effect of stresses in a structure subjected to cyclic loading at high frequency. A finite element formulation for thermo-elastic damping analysis has been proposed by Serra and Bonaldi [10]. The thermo-elastic damping is calculated from the irreversible flow of entropy due to thermal fluxes that have originated from the volumetric strain variations. The coupled field finite element equations are derived by considering small harmonic variations of displacement and temperature with respect to the state of thermodynamic equilibrium. Comparisons with analytical results for thin beams were shown to illustrate the performance of the coupled field elements. Similar study of finite element analysis of heat generation using ultrasonic thermography has been carried out by Saboktakin et al. [11]. They used 'Vibrothermography' a technique that allows for selective imaging of defects using thermal waves that is generated by ultrasound waves. The mechanism involved is frictional heating or hysteresis that turns a dynamically loaded defect into a heat source, which is identified by a thermography system. They developed a finite element model for an edge crack subjected to ultrasonic waves.

Though a number of studies have been carried out to investigate the horn profiles and their performance, not much work has been reported on the thermo-elastic behavior of horns and the effects of cyclic loads. This study reports the internal heating of the horn due to stresses from high frequency cyclic loads and analyses the failure of horns arising from thermo-elastic effects. Four horns of different materials but with same end dimensions were fabricated. The materials are aluminum, titanium, stainless steel and mild steel. The length of the horn depends on the material properties of the horn and therefore there is a variation in their lengths. The temperature developed in the horn during welding is captured using an infra-red camera (Fluke) and smart view software and the same has been simulated using the multi-physics software 'Comsol'. Stresses developed in the horn were determined using harmonic analysis and these stresses were used to study the effect of cyclic loads (using the 'fatigue' module of Ansys). The methodology