Ultrasonics 75 (2017) 9–21

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Effect of acoustic softening on the thermal-mechanical process of ultrasonic welding

Kunkun Chen, Yansong Zhang *, Hongze Wang

Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form 28 October 2016
Accepted 9 November 2016
Available online 10 November 2016

Keywords:
Acoustic softening effect
Thermal-mechanical analysis
Plastic deformation
Heat generation
Structure deformation

ABSTRACT

Application of ultrasonic energy can reduce the static stress necessary for plastic deformation of metallic materials to reduce forming load and energy, namely acoustic softening effect (ASE). Ultrasonic welding (USW) is a rapid joining process utilizing ultrasonic energy to form a solid state joint between two or more pieces of metals. Quantitative characterization of ASE and its influence on specimen deformation and heat generation is essential to clarify the thermal-mechanical process of ultrasonic welding. In the present work, experiments were set up to found out mechanical behavior of copper and aluminum under combined effect of compression force and ultrasonic energy. Constitutive model was proposed and numerical implemented in finite element model of ultrasonic welding. Thermal-mechanical analysis was put forward to explore the effect of ultrasonic energy on the welding process quantitatively. Conclusions can be drawn that ASE increases structural deformation significantly, which is beneficial for joint formation. Meanwhile, heat generation from both frictional work and plastic deformation is slightly influenced by ASE. Based on the proposed model, relationship between ultrasonic energy and thermal-mechanical behavior of structure during ultrasonic welding was constructed.

1. Introduction

The effect of ultrasonic energy on metal plasticity has been under investigation for decades [1–4]. The superimposed high frequency ultrasonic energy during tension and compression tests reduces the yield strength of metallic materials significantly, namely the acoustic softening effect (ASE). ASE is similar to thermal softening. Nevertheless, the process takes place without much heat. Experimental results have shown that when the same amount of softening is produced, the required ultrasonic energy is 10^7 times less than the thermal energy [1,2].

Researchers have been utilizing ASE into different kinds of manufacturing process since its first findings, for example, ultrasonic assisted upsetting [5], ultrasonic assisted metal tube drawing [3], ultrasonic assisted extrusion [6], ultrasonic consolidation [7], ultrasonic welding [8], etc. The consumed energy was reported to be drastically reduced with the superimposition of ultrasonic energy during manufacturing process. For example, USW of metals consumes much less energy and time than resistance spot welding and friction stir welding. The advantage of USW is especially obvious for the joining of dissimilar materials, such as copper to aluminum in the manufacturing process of battery electric vehicles (BEVs) [9].

USW is a rapid joining process during which high frequency ultrasonic energy is used to produce a solid-state joint between two pieces of metals [10]. A typical USW process is shown in Fig. 1. It consists of two main steps, clamping step and welding step. Specimens are placed between sonotrode and anvil. A certain force is applied by the sonotrode and the specimens get into intimate contact, as shown in Fig. 1(a). During the welding step, the sonotrode vibrates parallelly to the contact area in ultrasonic frequency. Ultrasonic energy is transferred from the sonotrode to workpieces. Bond comes into formation at the faying interfaces of specimens. Micro bonds gradually initiate at the faying interfaces and ally together to form a sound joint, as illustrated in Fig. 1(b).

The bonding mechanism of USW has been studied by numerous researchers for more than 50 years. Nevertheless, the process is still not fully understood [11]. Researches have put forward various mechanisms for the joining process, for example, mechanical interlocking [12], interdiffusion and recrystallization [13], generation of heat by friction and plastic deformation [14] and even melting [15]. Among all the proposed theories, heat generation and plastic deformation have generally been considered playing significant roles for the joint formation process [16]. Although it is generally

* Corresponding author.
E-mail address: zhangyansong@sjtu.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.ultras.2016.11.004
0041-624X/

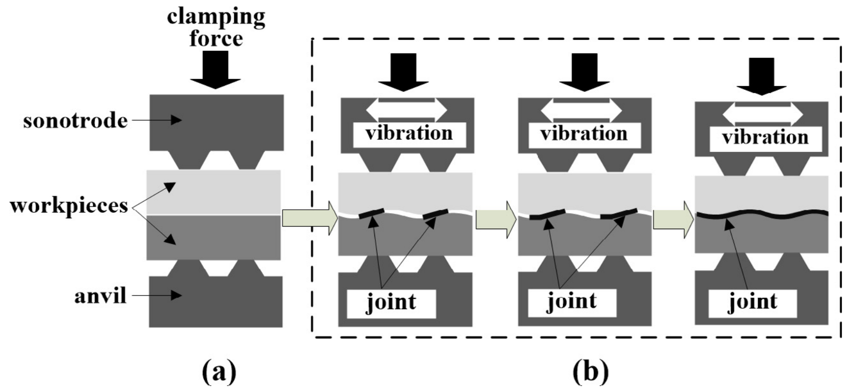

Fig. 1. An illustration of USW process: (a) clamping step and (b) welding step.

agreed that the maximum temperature does not exceed the melting points of welding materials, thermal effect due to heat generation from plastic deformation and frictional work can make huge influence on USW process [16]. During USW, workpieces make relative motion to each other at ultrasonic frequency. Tremendous heat is generated from frictional work between the contact interfaces. Meanwhile, under the combined effect of normal stress and vibratory shear stress caused by ultrasonic vibration of sonotrode, large areas of materials come into plastic deformation phase [17]. Proportional plastic deformation work will be converted to heat generation during the high strain rate process. Heat generation from these two sources (frictional work and plastic deformation work) leads to elevated temperature. Bakavos and Prangnell [18] conducted experiments of USW of aluminum. The temperature measured can reach nearly 400 °C, which leads to dramatic loss of material strength. They also concluded that joining proceeds by the development and spread of microwelds, until extensive plastic deformation occurs within the weld zone. Zhao et al. [19] measured the temperature at the sonotrode/specimen interface and concluded that the maximum temperatures during the welding process are sufficient enough to result in dramatic softening of the welding materials and complex metallurgical reactions. Prangnell et al. [20] measured the weld thermal cycles. The obtained data shows that USW results in extremely rapid heating rates and cooling rates of materials. Patel et al. [21] conducted experiments to find out the influence of USW on microstructure in magnesium alloy. The results indicated that localized plastic deformation and material flow at the contact area are critical factors for the initial formation of weld joints. Experimental results [18–23] show that localized frictional heating and plastic deformation at the contact area are critical factors for the initial formation of ultrasonic weld joints. A great deal of plastic deformation and material flow occurs across the faying interfaces of workpieces. Joint initially develops at specific regions under the tool, with plastic deformation highly localized at the contact interface of workpieces. USW can be concluded as a coupled thermal-mechanical process, during which heat generation and plastic deformation of materials should be considered as significant issues.

Therefore, it is of significant importance to study heat generation and structural deformation in order to gain a comprehensive understanding of USW process. However, it's difficult to obtain the real-time data of specimen deformation from experimental measurements due to transient nature of welding process [11]. Numerical simulation method, such as finite element method (FEM) can overcome these obstacles to some extent and has been employed by researchers in recent years. The work by Siddiq [24] and Ghassemieh [25] incorporated the materials' thermal softening effects into finite element model particularly. They adopted the material properties with extension for temperature dependence. The effect of welding parameters, such as applied load, vibration amplitude and sonotrode velocity on friction work and temperature distribution were analyzed. De Vries [26] and Elangovan et al. [27] analytically computed heat generation by friction and plastic deformation separately rather than considering the dynamic thermal-mechanical process. The presented finite element model took the calculated heat generation as boundary conditions. Temperature distribution and their influences on the workpieces, sonotrode and anvil were analyzed. Gao [28] characterized the interface friction conditions via a simple analytical model of elastic stress field. The calibrated model was capable of studying the material plastic deformation initiation and propagation, the slippage at the interface surface. Lee et al. [29,30] used the combined standard/explicit algorithm, incorporating with commercial software Abaqus to simulate dissimilar metal USW. They made assumptions by using the implicit algorithm to simulate the dynamic process for the goal of calculation time reduction. The procedure was used to predict welding energy and temperature distribution of the workpieces. Kim et al. [31] constructed a thermal-mechanical model of USW process, in which heat generation from plastic deformation was ignored. They found out that frictional heating has significant effect on the welding process and should be included in the analysis.

Comprehensive understanding of thermal-mechanical process requires accurate characterization of deformation behavior under combined thermal and acoustic softening effect. Thermomechanical plasticity of metals have been under study for numerous years from Swearengen [32] to Srivatsan et al. [33]. Various models have been proposed to represent mechanical behavior under different thermal conditions as described by Sih [34]. As for ASE, the fundamental mechanisms have not reached a consensus. There are three main views about ASE: energy absorption of dislocations proposed by Blaha [1], stress superimposition proposed by Winsper [35] and surface friction effects proposed by Pohlman [36]. Most of the time, the description of ASE was expressed by introducing a softening term related to ultrasonic energy in constitutive model. Acoustic softening term was obtained by characterizing ultrasonic energy induced specimen deformation in ultrasonic-assisted tension or compression experiments as illustrated by Yao et al. [37]. And then, traditional constitutive model was modified by incorporating the acoustic softening term. The introduced acoustic softening term expresses the enhancing effect of ultrasonic vibration on specimen deformation.

Much work has been done by predecessors and valuable conclusions have been obtained through numerical analysis of USW process. But most of the time, the proposed models have not considered the coupled thermal-mechanical process and ASE