Design and production of pressure vessel for food processing machine using underwater shock using measurement of particle velocity and results of numerical analysis

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ABSTRACT

Okinawa National College of Technology has developed a food processing machine using underwater shock waves. Several prototype machines were developed, and experimental results (sterilization, improvement of juice extraction, milling flour, emulsification etc.) were obtained. After deciding food materials to be processed and the desired processing results, we designed and manufactured a pressure vessel for experiments. In this report, the process flow for designing and manufacturing a pressure vessel for softening meat using underwater shock and its concept design are described. The relationships among the number of shock waves, the distance between the shock wave generation point and the meat, the backing material, and the amount of softening ware experimentally compared. We measured the velocity of the shock wave penetrating to the inside of the meat, from which we estimated the particle velocity. We developed computer simulation model using the estimated particle velocity in the meat. Using the results of the analysis obtained from the computer simulation model, we designed and fabricated the pressure vessel.

1. INTRODUCTION

In advanced nation, the consumptions of the edible meat increase [1-3]. There have been many studies on the tenderness of food [4-5]. Tenderness is one of the most important sensory characteristics of meat. The conventional method of tenderness meat are cutting muscle fibers with a knife or Biological method etc. [6]. It is shown that the softening of the meat using hydrodynamic shock wave. However, hydrodynamic shock wave is produced by an explosive and is unsuitable for practical use [7]. Biochemical techniques have shown the possibility of tenderness of meat [8-12].

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National Institute of Technology, Okinawa College has developed a food processing machine using underwater shock waves [13-18]. Several prototypes machines were developed, and experimental results (sterilization, improvement of juice extraction, milling flour, emulsification etc.) were obtained. After being requested by a meat processing company to develop a pressure vessel for softening ham, we designed and manufactured a pressure vessel the basis of the results of fundamental experiments, the estimation of particle velocity, and a computer simulation model. In this report, the flow of research for designing and manufacturing the pressure vessel is described. The softening experiment carried out in accordance with the research method, the measurement of the particle velocity in meat, the creation of a numerical analysis model, and the prototype pressure vessel based on the results are reported.

2. PROCESSING MECHANISM BY SHOCK WAVES

Figure 1 shows the processing using shock waves. When the shock wave penetrates inside the food, it splits into a reflected wave and a transmitted wave at the pressure interface. The food is broken up by the pulling force at the dividing point. This destruction is commonly known as the spalling-phenomenon and, it destroys cell walls. Figure 2 shows an overview of the food processing device that generates underwater shock waves. Electric energy is charged by a high-speed charging device (TDK Lambda: 152A) from a switchboard (200 V, 20 A). The pressure vessel for food processing is filled with water. The charged electric energy is supplied to an electrode in the pressure vessel by a gap switch with an air cylinder. A thin aluminum wire is installed between electrodes, and it is evaporated by the thermite reaction induced by the instantaneously applied high voltage, resulting in shock wave generation. The generated shock wave propagates through the water in the pressure vessel. The food to be softened is packed in the pressure vessel with silicone or resin. The food is broken up at the interface owing to the density difference, resulting in spalling-phenomenon. The meat is processed (softened) by this phenomenon.

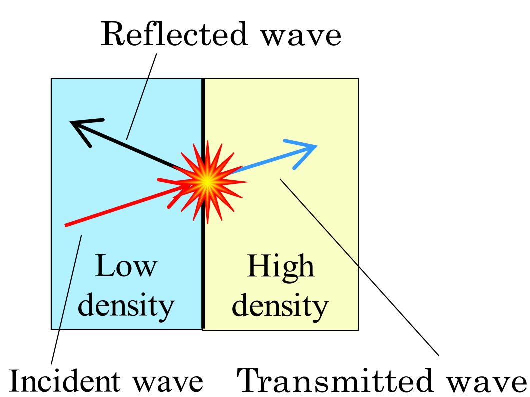


Fig.1 Spalling destruction

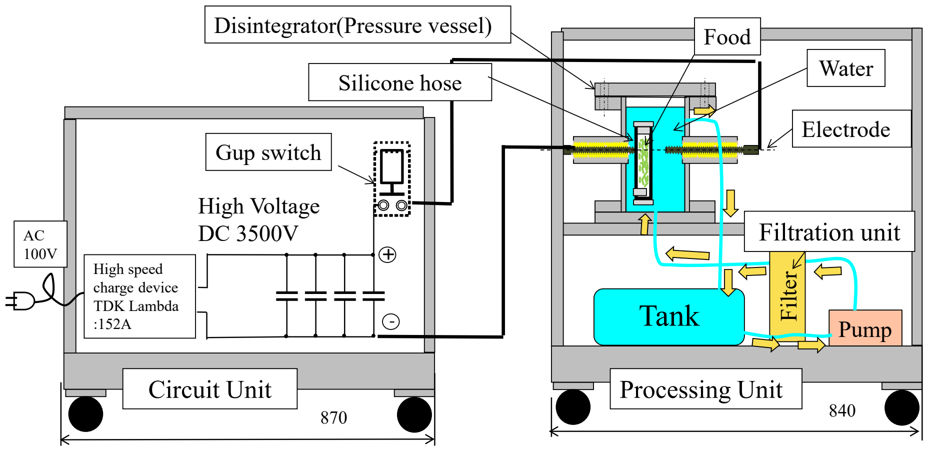


Fig. 2 Cross section of food processing device

3. DESIGN AND PRODUCTION OF PRESSURE VESSEL BY RESEARCH FLOW

3.1 Research flow

When we are requested to develop a pressure vessel for processing new foods, we design and manufacture the pressure vessel on the basis of the results of fundamental experiments, the estimation of particle velocity, computer simulation models. In this report, we describe newly designed equipment for softening meat (pork). Figure 3 shows the flow of the research. First, the concept design of the pressure vessel is created. We carry out test processing with the developed pressure vessel, and reveal the relationship between the processing conditions and the results of processing using shock waves. The experimental results provide the basic dimensions for the design of the pressure vessel. To estimate the particle velocity, the velocity of the shock wave passing through the inside of the meat is measured, and the particle velocity is estimated using this velocity. We develop the computer simulation model for processing meat using the estimated particle velocity and design a pressure vessel on the basis of the simulation result. Figure 4 shows the conceptual design of the pressure vessel for softening meat. A shape of ham is typically cylindrical with a size of about Φ 100 mm × 1 m. A pressure

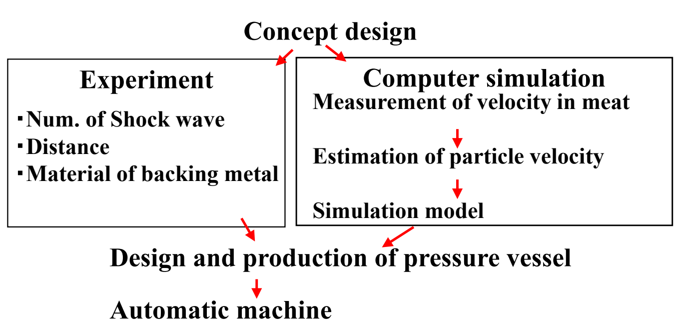


Fig. 3 flow of research

vessel that can process meat of this shape is designed. To determine the dimensions of the pressure vessel, which greatly affect the processing effect of the shock waves, we varied the number of shock waves, the distance from the point of shock wave generation to the meat, and the backing material to experimentally clarify their relationships with the softening of meat.

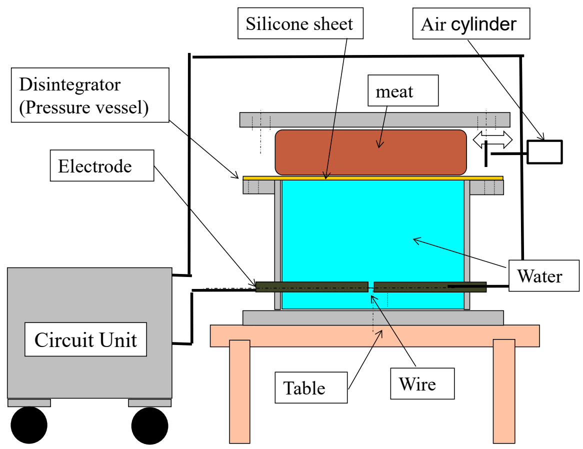


Fig. 4 Conceptual design of the pressure vessel for softening meat

3.2 Processing experiment

Figure 5 shows the experimental conditions. The material of the wire used is aluminum with a diameter of 1 mm and a length of 8 mm. The electric energy used to generate the shock waves is 4.9 kJ. The size of meat has a width of 100 mm, a depth of 40 mm, and a thickness of 10 mm. The initial distance between the point of shock wave generation and the meat was set to 135 mm. The number of shock waves was varied from 1 time to 3 times. The distances between the point of shock wave generation and the meat are the initial distance (135 mm), 85 mm, and 185 mm. The material of the backing material is none (water), wood, or stainless steel (SUS 303). Experiments were carried out using a previously produced pressure vessel for visualization, the softening value the meat was measured with a durometer (type OO) [19]. The food color was measured at several points, intervals of 10 mm. The durometer hardness was measured five times at each measurement point, and a total of 35 measurement results were obtained which were averaged. Figure 6(a) shows the relationship between the durometer hardness (tenderness) of the meat and the number of shock waves. Figure 6(b) shows the relationship between the hardness of meat and the distance between the point of shock wave generation and the meat. As the distance decreases, the meat clearly becomes more tender, negative hardness value indicates that the meat has been softened. The hardness of the meat increased alter processing with a single shock wave, the third shock wave the meat had been softened by about 1.8 fold.

In other processing experiments (extraction and flour milling) processing with a single shock wave also had a negative effect [20-21]. It will be necessary to clarify the reason why the meat became harder after processing with a single shock wave by microscopic observation. Figure 6(c) shows the relationship between the hardness and the reflectance of the backing material with water. The acoustic impedance which determines the reflectance is calculated by multiplying the density of the meat and the speed of sound. The reflection of the shock wave depends on the backing material, and it is assumed that this caused in the hardness of the meat. The effect of the backing material on the tenderness was found to increase with the number of shock waves and the distance between the meat and the point of shock wave generation. We can manufacture a pressure vessel for tenderizing meat by setting the distance between the meat and the point of shock wave generation, the backing material, and the transport speed of meat calculated from the charging time and the number of shock waves in accordance with the desired hardness (tenderness) measured using a durometer.

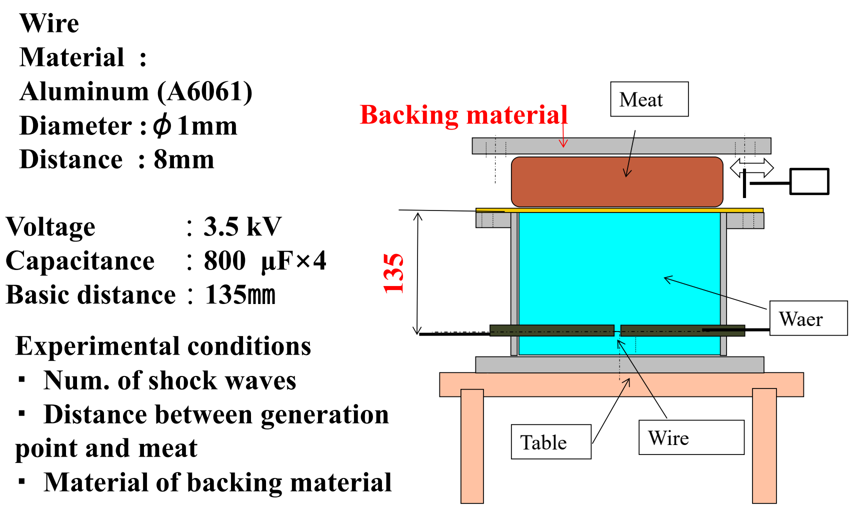
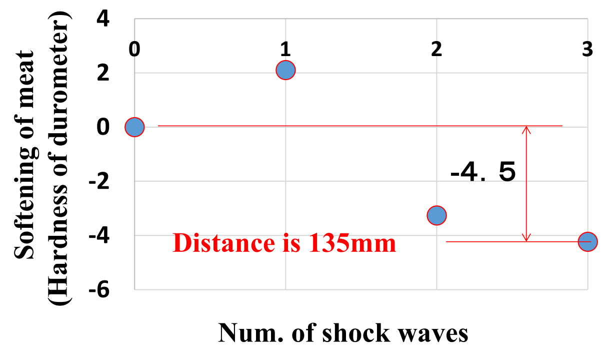


Fig. 5 Experimental conditions

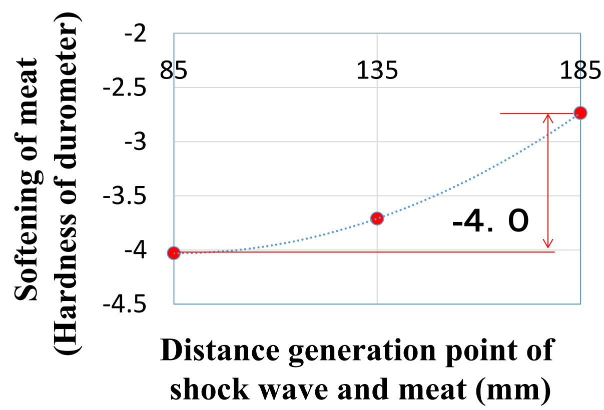
3.3 Measurement of particle velocity and numerical simulation

To measure the particle velocity of the shock wave propagating in the meat to be processed, the velocity of the shock wave propagating through the meat was measured. Figure 7 shows the setup of the experiment carried out for optical observation. The upper part of the setup is an explosive lens, which enables the generation of parallel shock waves in the downward direction. We observe the shock wave inside acrylic with a high-speed camera to elucidate the relationship between the propagation distance and propagation time. Figure 8 shows the obtained relationship where yellow region in the center of the figure corresponds to the position of the meat. The velocity of the shock wave propagating through the meat is estimated by the least-squares method. The particle velocity is calculated by Equation 1 (Rankine-Hugoniot equation) using the estimated velocity. Equation 1 shows the Us and Up. Up is estimated meat particle velocity and, Us is shock wave velocity.

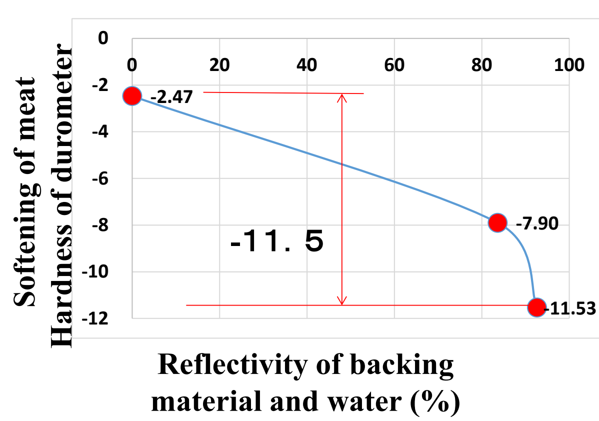
$$\mathrm{Us} = 1.535 * \mathrm{Up} + 2.5867 \tag{1}$$



a Number of shock waves



b Distance between meat and generation point



c Backing material

Fig.6 Experimental results of relationship between processing conditions and hardness (softness) of meat

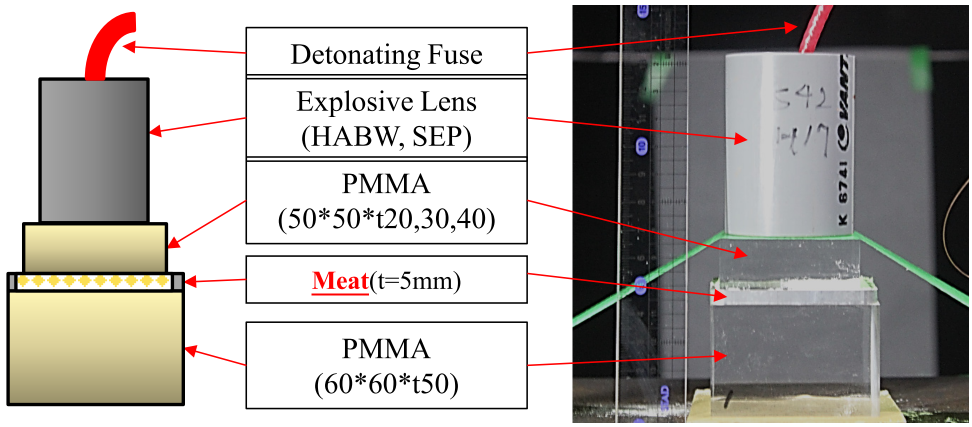


Fig. 7 Setup of experiment for optical observation

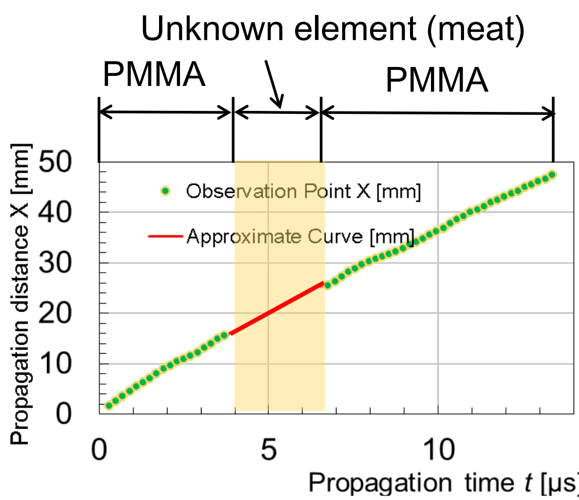


Fig. 8 Obtained relationship between propagation distance and propagation time

4. DEVELOPMENT OF NUMERICAL ANALYSIS MODEL AND PRODUCTION OF PRESSURE VESSEL

We developed a numerical analysis model using the estimated particle velocity. Hyper Works Software was used for the simulation. Figure 9 shows the computer simulation model. The number of quadrilateral elements is 98,896 and the number of nodes is 99,681. Table 1 shows the physical quantities parameters used in this simulation. The parameter ρ is the density, E is compressive strength, C is speed of sound, Z is Acoustic impedance [14]. Figure 10 shows the pressure of the shock waves transmitted to the meat in the upper part of the pressure vessel in the analytical model. The deformation of the stainless steel due to the shock wave pressure remains within the region of elastic deformation, indicating that the pressure resistance of this vessel is sufficient. We manufactured a pressure vessel based on the design drawings. Figure 11 shows the manufactured pressure vessel. The thickness of the pressure vessel was 7.6 mm and the material used was SUS304. A silicone hose with an inner diameter of 100 mm and an outer diameter of 110 mm penetrates the container, and the meat inside the vessel is processed by shock waves. The meat was experimentally processed in this vessel, and the results confirmed that meat could be softened by the shock waves without any problems.

Table 1 Parameters used in simulation

Parameter	Meat	Silicone
P (kg/m^3)	15.9	1070
E (MPa)	77.1	70.8
C (m/s)	1558	1485
Z × 10^6 ($kg/(m^2s)$)	1.652	1.590

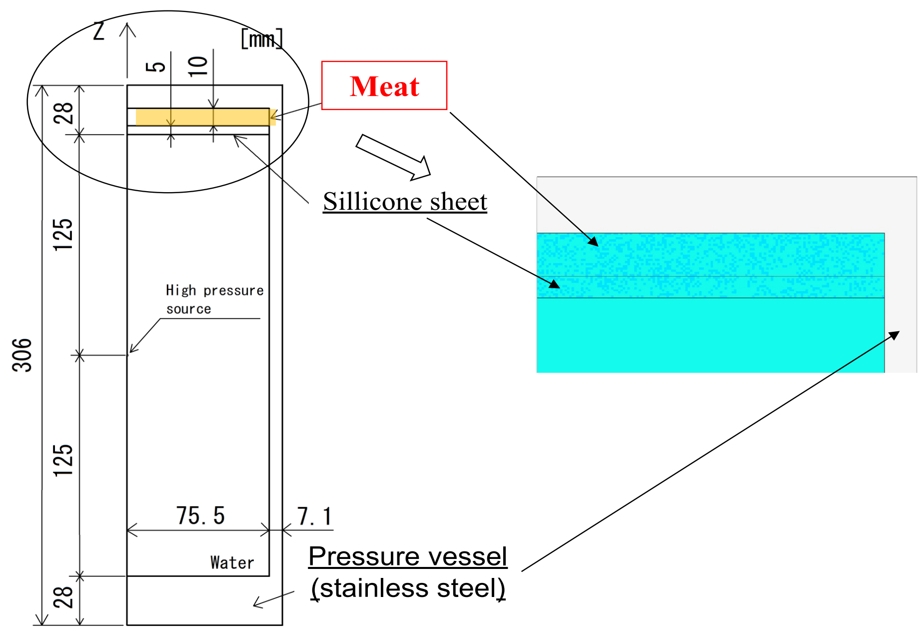


Fig.9 Model used in simulation

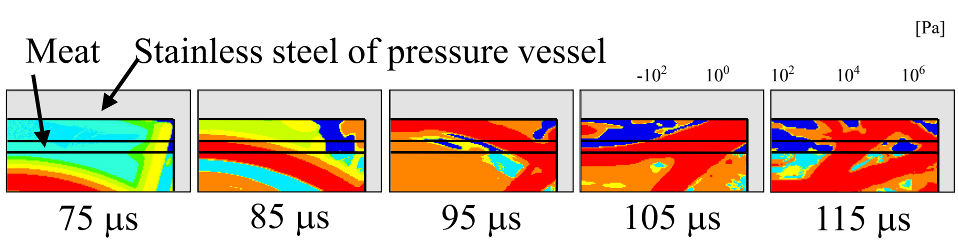


Fig. 10 Results of computer simulation

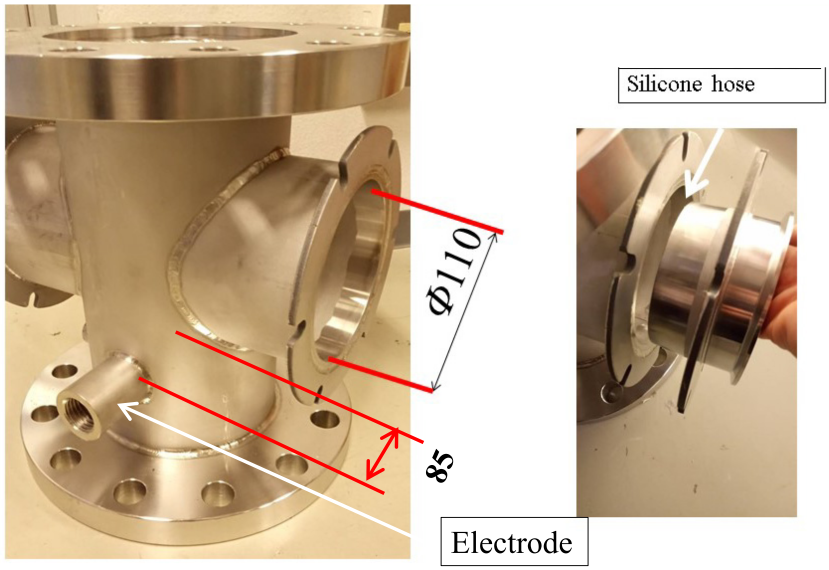


Fig.11 Photographs of pressure vessel for softening meat

5. CONCLUSION

The research flow for creating a pressure vessel for use in food processing equipment for meat softening was presented. In accordance with the research flow, meat was processed experimentally in the pressure vessel using shock waves. The relationship between the amount of softening and the shock wave generation conditions was experimentally examined by varying the processing conditions. The propagation velocity used to estimate the particle velocity in meat was measured by optical observation, and a model for numerical analysis was developed. The pressure vessel for meat softening was designed and manufactured on the basis of the numerical analysis results and the pressure resistance of this vessel is sufficient. The research flow for developing a pressure vessel to soften meat and the possibility of its development in accordance with the flow were demonstrated.

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