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Feasibility Study of Cryogenic Cutting Technology by Using a Computer Simulation and Manufacture of Main Components for Cryogenic Cutting System

컴퓨터 시뮬레이션을 이용한 극저온 절단 기술 적용성 연구 및 극저온 절단 시스템 주요 부품 제작

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Abstract

Cryogenic cutting technology is one of the most suitable technologies for dismantling nuclear facilities due to the fact that a secondary waste is not generated during the cutting process. In this paper, the feasibility of cryogenic cutting technology was investigated by using a computer simulation. In the computer simulation, a hybrid method combined with the SPH (smoothed particle hydrodynamics) method and the FE (finite element) method was used. And also, a penetration depth equation, for the design of the cryogenic cutting system, was used and the design variables and operation conditions to cut a 10 mm thickness for steel were determined. Finally, the main components of the cryogenic cutting system were manufactures on the basis of the obtained design variables and operation conditions.

Key words : Cryogenic cutting technology, Smoothed particle hydrodynamics, Cryogenic jet penetration depth equation

요 약

극저온 절단 기술은 절단 과정에서 2차 폐기물이 발생되지 않기 때문에 원자력 시설의 해체기술로 가장 적합한 기술 중 하나이다. 본 논문에서는 SPH 기법과 FEM 기법을 혼합한 하이브리드 기법을 이용한 컴퓨터 시뮬레이션을 통해 극저온 절단 기술의 적용성을 파악하였다. 또한 극저온 절단 시스템의 설계에 활용하기 위해 절단 깊이 예측식을 사용하여 스틸 10 mm 두께를 절단하는데 필요한 설계 변수 및 운전조건을 도출하였다. 마지막으로 도출한 설계변수 및 운전조건을 기반으로 극저온 절단 시스템의 주요 부품을 제작하였다.

중심단어 : 극저온 절단 기술, Smoothed particle hydrodynamics, 극저온 절단 깊이 예측식

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I. Introduction and Background

Recently many countries have become interested in decommissioning nuclear facilities due to the increasing number of obsolete nuclear facilities. Until now, dismantling technologies have mostly been traditional technologies such as a mechanical cutting (shear, nibbler, wheel saw, milling etc.) and a thermal cutting (plasma, oxy-fuel burning, laser, etc). However, serious problems such that most of the traditional technologies produce a lot of secondary waste during a cutting process in a radioactive environment have arisen. So, the introduction of advanced dismantling technologies is urgently needed for the development of an efficient machining method applicable to a hazardous environment such as nuclear facilities and an explosive area.

Cryogenic cutting technology as a new cutting technology has been studied. This cryogenic cutting technology cuts using high-pressure liquefied gas jets of substances such as ammonia, CO_2, and LN_2. Cryogenic cutting technology offers a number of potential advantages over the conventional cutting methods. These include the following:

- Elimination of liquid residue, since these substances are gaseous at room temperature and atmospheric pressure. This is very desirable, both in environments that must be kept very clean and in applications where the workpiece contains highly toxic or radioactive materials. In the former case, a workpiece contamination can be minimized, while in the latter, hazardous waste disposal problems may be mitigated.
- Potential extension of a jet cutting to applications in which fragile equipment or materials are located downstream of the intended workpiece surface. The cutting power decreases rapidly with the downstream location, due to the rapid broadening of a jet's axial momentum flux distribution as the liquid vaporizes.
- Potential for the use of volatile solids such as CO_2 as an abrasive material within a jet to augment a cutting or cleaning performance, further reducing the volume of residual material to be removed and processed.
- Possible modifications in the failure mode of a workpiece material, due to a decrease in its temperature to below its ductile/brittle transition temperature.

Researches related with a cryogenic jet are as follows and have tended to use fluid media. Firstly, among the thermodynamically unstable fluids, the most practical application is found for carbon dioxide. The feasibility of applying cryogenic CO_2 for a machining and an examination of a material removal was carried out by a few researchers [1-2]. A process was developed to demonstrate a cryogenic removal of coatings and contaminations from substances' surfaces. It involved the use of solid pellets of carbon dioxide as the blasting medium. It was shown that the material was removed as a result of a thermal shock action of the pellets in addition to an abrasive contribution. It was claimed that the employed cryogenic blasting process was able to remove organic coatings and a contamination from substances. Secondly, ammonia has been used for years as a cryogen in different applications. Recently, however, liquid ammonia was demonstrated to be useful in efficiently and rapidly demilitarizing rocket motors [3]. Energetic ingredients such as AP(Ammonium perchlorate), HMX(High melting point explosive) and RDX(Royal demolition explosive) are soluble in ammonia and thus, can be washed out. Gel and solid rocket propellant can be physically and chemically ablated from motors using a liquid or gaseous reagent such as anhydrous ammonia. It has been projected that the high pressure ammonia jets can be used to cut steel and aluminum rocket casings. Thirdly, Dunsky and Hashish [4] demonstrated the thermodynamics of a liquid nitrogen jet formation when the fluid was adiabatically throttled through an orifice. Cooper [5] used cryogenic liquid nitrogen for drilling ground in unconsolidated formations. And also liquid nitrogen was used in milling experiments to increase a tool's life by using it as a cryogenic cooling medium. It was also shown that the use of liquid nitrogen for a cooling effect during a grinding increases a tool's life [6-7]. A different type of research was also undertaken to atomize liquid metals by the use of liquid nitrogen [8]. The results indicated that as the pressure increased, the size of the super fine particles decreased and they were observed to be spherical.

In this paper, by using a computer simulation, the applicability of cryogenic cutting technology was analyzed.

In the computer simulation a hybrid method that was combined with the SPH (smoothed particle hydrodynamics) method and the FE (finite element) method was used. And also, a penetration depth equation for the design of the cryogenic cutting system was used to determine the design variables and operation conditions to cut a 10 mm thickness for steel. Finally, the main components of the cryogenic cutting system were developed by using the obtained design variables.

II. Cryogenic Cutting Simulation

A cryogenic cutting simulation has been regarded as a fluid-solid impact problem. A few researchers [9-12] have tried to solve this related problem by using a finite element analysis (FEA)[13-14] to calculate the stress and the displacement of a target and a flow. But this approach only obtains reasonable results in the small deformation cases and if it is applied to a large deformation case it leads to a mesh distortion in the FEA. For example, a numerical simulation of a high-velocity waterjet action on a target was studied in reference [9]. It employed the FEM and ALE (Arbitrary Lagrangian/Eulerian) methods to study the interactions between a waterjet and a target. But this approach also distorted some grid meshes and moreover the ALE formulation required much computational time due to an additional computational field.

To overcome the above difficulties, a hybrid method which was coupled a smoothed particle hydrodynamics (SPH) with a FEA was introduced. The computation process of this method was in the frame of a Lagrangian description so it made the computation time a more compact process. The hybrid method includes two aspects: firstly, it represents a coupled model of the SPH particles and the finite elements; secondly, these two different discrete parts interact by using a contact algorithm of "nodes to surface".

The SPH method was first introduced by Lucy [15] and Gingold & Monaghan [16] in 1977 in order to study fission in rotating stars. The SPH is one of the mesh-free particle methods and is increasingly being used to model a fluid motion. By the SPH method, a continuous material such as a fluid is expressed by a set of discrete elements, referred to as particles, which carry some physical quantum such as a mass and velocity. Since there is no mesh structure among these particles, the distortion of a mesh can be avoided. Johson et. al. [17] presented the basic SPH computation algorithm, applied to high velocity impacting problems and obtained encouraging results.

This paper used the hybrid method combined with the SPH method and with the FEA method to simulate the penetration process of cryogenic cutting technology. The liquid nitrogen and abrasive were modeled by SPH particles and the target metal was modeled by finite elements and also the jet velocity distribution was assumed as uniform.

1. Theory of the SPH

As mentioned above, using the SPH, the fluid is represented by particles. Each particle has a fixed mass and follows the fluid motions. The conservation equation governing the evolution of the fluid is expressed as inter-particles when written in the SPH form. Each particle carries a mass , velocity , and other quantities specific to a given problem. The equations governing the evolution of the mechanical variables are expressed as a summation of interpolants using a kernel function with a smoothing length . For example, Eq. (1) shows the mass conservation equation is given by

$$\frac{d\rho}{dt} = -\rho \nabla (v) \quad \text{(1)}$$

which can be evaluated with the following SPH approximation :

$$\frac{d\rho}{dt}(x_i) = \sum_{j=1}^{N} m_j [v(x_j) - v(x_i)] A_{ij} \quad \text{(2)}$$

The SPH momentum equation may be written as :

$$\frac{dE}{dt}(x_i) = -\frac{P_i}{\rho_i^2} \sum_{j=1}^{N} m_j [v(x_j) - v(x_i)] A_{ij} \quad \text{(3)}$$

Figure 1 shows the simulation process of the hybrid method. In Figure 1, the upper part represents the computational process of the SPH and the lower part represents the FEA process. In the SPH part, the velocity and position of the particles are calculated at first, then the variable smoothing length and neighboring search are performed, and then the strain, stress, and forces of the

SPH are calculated. The SPH and FEA are connected by nodes to a surface contact algorithm so if the SPH nodes are contacted to an FEA surface, the contact force of the FEA is calculated, and then a determination of the displacement, strain, and stress of the FEA are followed.

2. 3D Model and Mesh

Liquid nitrogen and an abrasive with a high velocity were impacted on the target material, and the size of the liquid nitrogen jet was a cylinder shape of diameter 1 mm × length 40 mm. The metallic target was a 3-D block with a rectangular area of 10 × 10 mm^2 and a thickness of 10 mm.

Figure 2 shows the 3D mesh of the liquid nitrogen and the abrasive. The liquid nitrogen jet mixing with the abrasive was meshed by the SPH with a diameter of 1 mm and the total number of particles was 5,771, impacted on the target with a velocity of 300 m/s. The target material had a size of 30 mm × 15 mm × 10 mm, meshed by FEA and it had 41,600 elements.

3. Material Property

Steel 4340 was chosen as a metallic target material and garnet was also used as abrasive. Actually the jet fluid was combined with the liquid nitrogen abrasive, so in order to define the density of the fluid, an equivalent density was introduced. Generally, among a mixed jet fluid, water accounts for 84 % and an abrasive accounts for 16 %. From that data, the equivalent density of the liquid nitrogen and the abrasive are calculated by the following

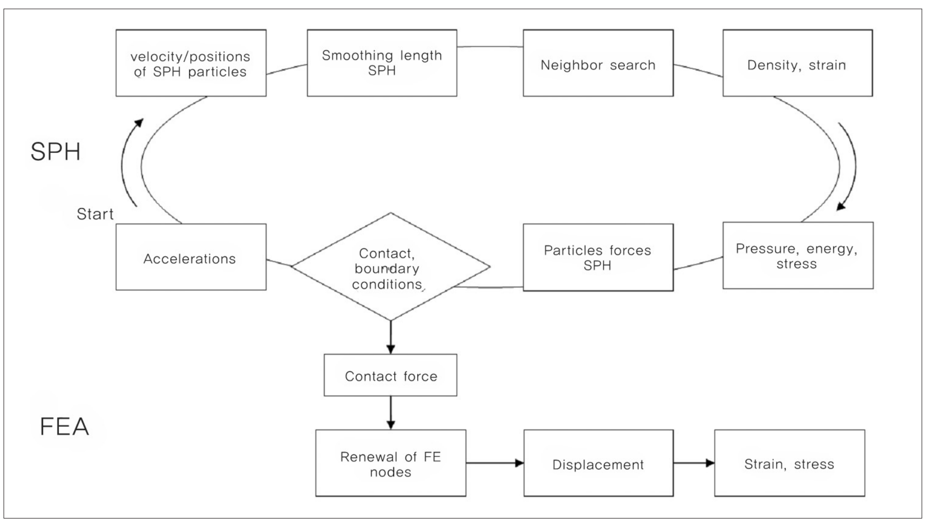

Fig. 1. Simulation process of the hybrid method

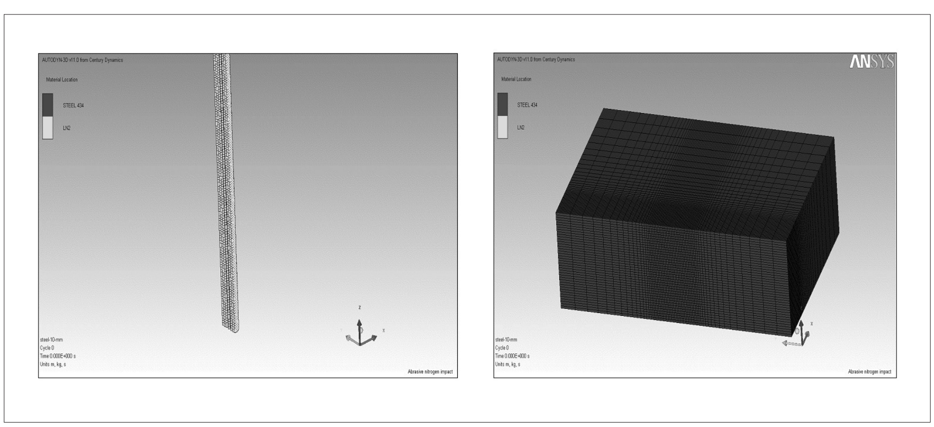

Fig. 2. Numerical model for target (FEA) and liquid nitrogen and abrasive (SPH)

equation (4) :

$$\rho_{eq} = \rho_{LN2} \times V_{LN2} + \rho_{abrasive} \times V_{abrasive} \quad (4)$$

where P_{eq} is the equivalent density of the jet fluid, the density of the liquid nitrogen(604 kg/m^3), $P_{abrasive}$ the density of the abrasive(3,400 kg/m^3), V_{LN2} the volume portion of the liquid nitrogen and $V_{abrasive}$ the volume portion of the abrasive.

Numerical erosion is a technique used in Lagrange codes in order to handle severely distorted zones that appear in, for instance, in penetration problems. These zones are deleted (eroded) when a suitably defined effective strain exceeds a pre-set value and the erosion strain value. In this study, an instantaneous geometric strain was used and the instantaneous geometric strain for steel 4340 was equal to 1.0.

4. Simulation Results

Cryogenic cutting simulation is an impact simulation where a fluid mixing with liquid nitrogen and an abrasive is impinging against a target at 300 m/s. Simulation was done during 1 ms and the results were obtained every 0.001 ms. (a) ∼ (f) in Figure 3 present the results of the cryogenic impact simulation. In Figure 3 (d) at 0.1 ms, the liquid nitrogen jet penetrated a 10 mm steel plate. We can estimate the liquid nitrogen pressure by using the Bernoulli Eq.(5) and the liquid velocity.

$$gdh + \rho_f^{-1} dp + d(0.5v^2) = \text{constant} \quad (5)$$

The pressure of the liquid nitrogen jet flow can be estimated by equation (6) :

$$v = \mu p_v \sqrt{2p_0/\rho_f} \quad (6)$$

Here, g is the gravity, h the absolute height, P_f the density of the fluid, P_0 the static pressure and the flow velocity. The parameters μ and P_V are reduction numbers and consider the velocity losses due to friction on the nozzle walls and in the transport hoses, respectively. The factor μP_V was estimated to be 0.9. On the basis of equation (6), we estimated the pressure to be 300 MPa.

III. Cryogenic Cooling System Design

In Chapter II, we established the feasibility of cryogenic cutting technology by using the computer simulation. In this chapter, the determination of the performance variables and the operation conditions are described.

The performance variables of the cryogenic cutting technology are the fluid pressure, the abrasive feed rate, the stand-off distance and the nozzle feed rate. In addition, the material properties, the abrasive properties etc. are also important variables that affect the cutting depth. Therefore, in order to determine the performance variables and the operational variables, a cutting depth model needs to be derived, and the variables suitable for cutting a steel to a 10 mm thickness need to be determined, and then the specifications of the cryogenic cutting system need to be determined.

1. Cryogenic Cutting Depth Estimation Model

Cryogenic cutting technology is similar to waterjet cutting technology and the only difference is the jet fluid, i.e. water and liquefied gas. Many researchers have developed cutting depth estimation models for a waterjet and have proposed their unique models. Especially,

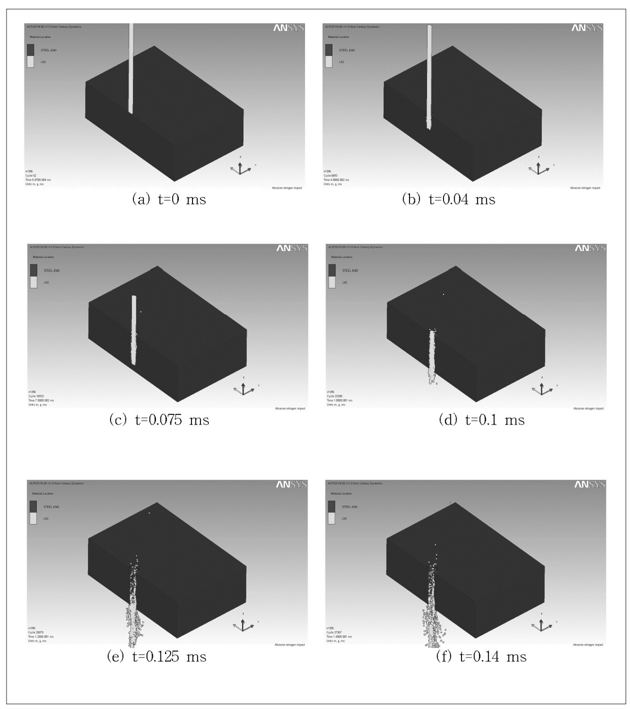

Fig. 3. Liquid nitrogen jet cutting simulation results with time

Hashishi [19] developed the first theoretical abrasive waterjet cutting model in the world and then Zeng and Kim and Momber [20-21] proposed their cutting models. However since these models are only focused on a waterjet, they do not consider the liquefied gas effects like ammonia, CO_2 and liquid nitrogen on the cutting depth as the fluid changes the temperature of the target. Recently Wang [22] developed predictive mathematical models for the depth of a cut during an AWJ(Abrasive Water Jet) cutting. He defined the cutting depth model as a combination of several dimensionless variables with performance variables affecting the cutting depth. Constants and exponents of the dimensionless variables were determined by a regression method through an experiment. This model contained the flow stress and hardness of a target material which are affected by a temperature drop of the target. In this study, performance variables and operational conditions were determined by using the predictive model proposed by Wang modified for a liquid nitrogen jet.

Eq. (7) shows the predictive cutting depth model for the liquid nitrogen jet by modifying the predictive cutting depth model for a waterjet presented by Wang.

$$h = 14.9 \times \frac{m_a P}{\sigma_f \rho_n u d_j} \left(\frac{D}{H}\right)^{0.156} \left(\frac{P}{\sigma_f}\right)^{0.186} \left(\frac{H_d}{E}\right)^{0.17} \quad (7)$$

where m_a is the abrasive mass feed rate (g/s), P is the fluid pressure (MPa), σ_f is the material flow stress (MPa), P_n is the liquid nitrogen density (g/mm²), d_j is the nozzle diameter (mm), D is the average particle diameter (mm), H is the stand off distance (mm), H_d is the material dynamic hardness (MPa), and E the elasticity modulus (MPa).

2. Performance Variables and Operational Conditions

To obtain the design variables and operational conditions on the basis of Eq. (7), the initial input data for a target and a fluid are required. The initial input values used in Eq. (7) are follows : material flow stress, σ_f is 1,800 MPa, material dynamic hardness, H_d is 2,459 MPa, modulus of elasticity, E is 159,000 MPa for a target material and liquid nitrogen density, P_n is 0.604 g/mm².

Among the design variables, the determination of the

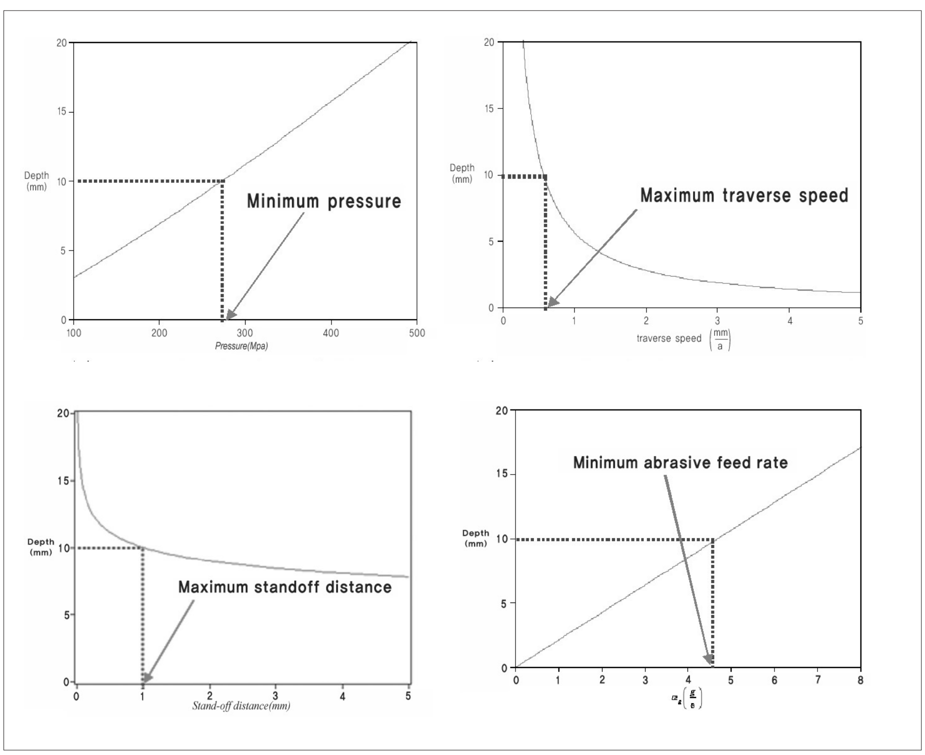

Fig. 4. Penetration depth plot with respect to design variables

fluid pressure is important due to a high pressure component design in a cryogenic cutting system and the other important variables are the traverse speed, stand off distance, and abrasive flow rate for setting the operational conditions of cryogenic cutting system. Therefore, to obtain the important factors, the cutting depth plots with respect to each design variable variation are drawn, as shown in Figure 4. In Figure 4, we found that for cutting a 10 mm target material, the minimum fluid pressure is 300 MPa, the maximum nozzle speed is 0.7 mm/s, the maximum stand-off distance is 4 mm and the minimum abrasive mass flow rate is 4.7 g/s.

IV. Development of a Cryogenic Cutting System

1. Configuration of the Cryogenic Cutting System

As seen in Figure 5 the configuration of the cryogenic cutting system is mainly composed of a liquid nitrogen tank, a high pressure component, an attenuator, a nozzle, and a pipe. The cutting process is as follows:

The liquid nitrogen in the storage tank is moved to the inside of both cylinders in the high pressure system by the internal pressure (1∼2 kg/cm^2) of the storage tank. After both cylinders are filled with liquid nitrogen, the pistons apply the liquid nitrogen pressure by using a hydraulic motor. Pressurized liquid nitrogen moves to the attenuator through the pipe and then moves to the nozzle and it is mixed with the abrasive inside of the nozzle, and then the mixed fluid passes through a 0.1 mm orifice, and then the fluid is projected with a high velocity onto the target.

2. Description of Main Components

① Intensifier

The pressure generation system must deliver a constant and continuous flow of high pressure liquid nitrogen. For a low to a high pressure, an indirect pressurization of an intensifier is usually used to generate pressures over 300 MPa. In an intensifier, two cylinders with different inner diameters are coupled by their pistons. The piston with the largest diameter is driven by a low pressure hydraulic system with normally 5 to 30 MPa. The cylinder, as shown in Figure 5, produces a higher pressure corresponding to the ratio of the cross sectional areas of the pistons. This ratio is between 1:10 and 1:24, which results in liquid nitrogen pressures up to 300 MPa. Figure 6 shows a double acting intensifier. Two intensifiers are directly connected and work alternately, while one intensifier unit delivers the pressurized liquid nitrogen to the system, the other unit is refilled.

② Attenuator

The pressure drops each time at the end of an active stroke in the intensifiers due to the reciprocating action of the intensifiers and the compressibility of the liquid nitrogen

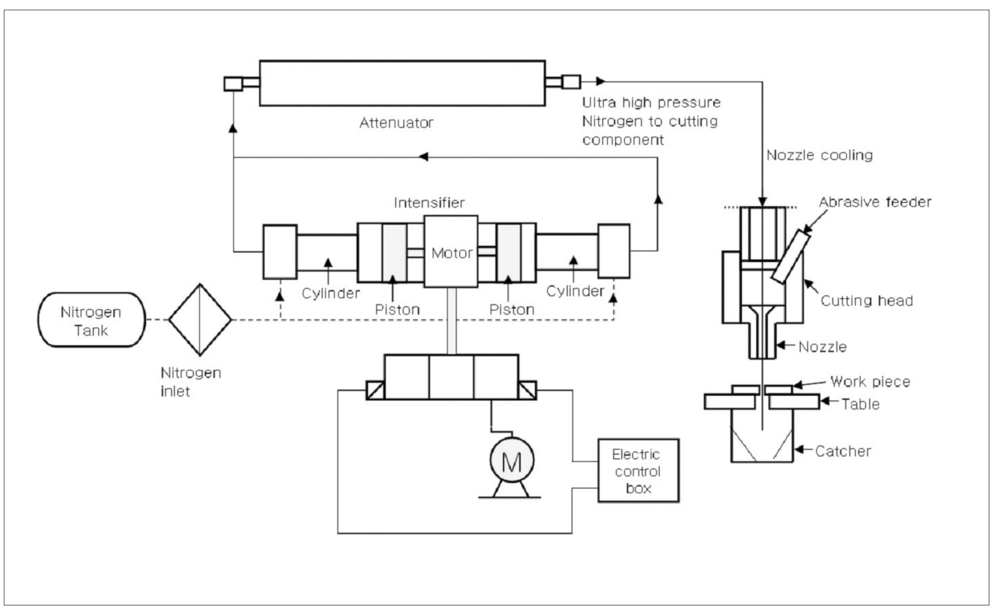

Fig. 5. Flow diagram of cryogenic cutting system

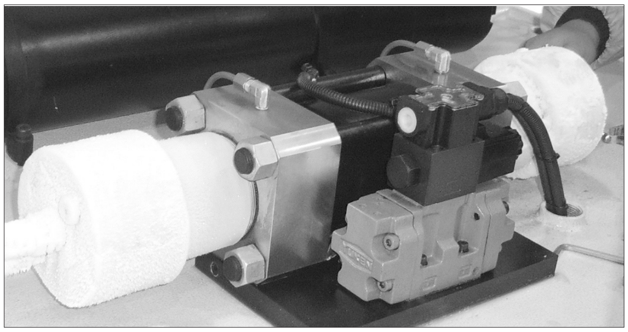

Fig. 6. Double acting intensifier

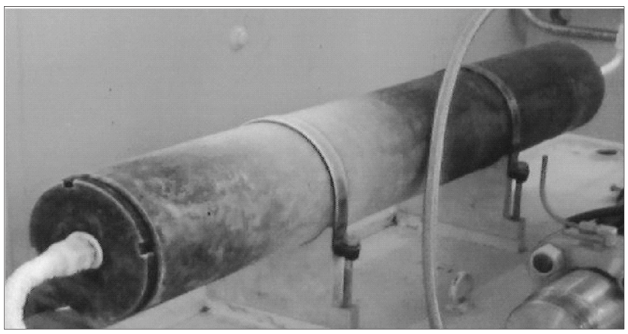

Fig. 7. Attenuator device for removing pulsating wave

at 300 MPa. This causes unacceptable pressure fluctuations in a double acting intensifier, which gives rise to cutting inaccuracies and shortens the life time of system components like the seals, valves and orifices as a consequence of the induced fatigue cycle. An attenuator is installed in the high pressure circuit to damp the influences of the pressure fluctuations.

③ **Pipe and nozzle**

Pipes are used to deliver the liquid nitrogen and they are made of STS 304 of a 3.5 mm thickness to endure a high pressure. A nozzle is used to convert the hydraulic energy of the pressurized liquid nitrogen into the kinetic energy of the liquid nitrogen. In the nozzle, at the end of the high-pressure tubing, an orifice is installed, which consists of a sapphire, a ruby or a diamond part with a hole of 0.08 to 0.8 mm inner diameter, mounted in an aluminum housing. Through this orifice, a high-pressure liquid nitrogen is expelled and a pure liquid nitrogen is formed, which is let into the mixing chamber. Through the interaction of the pure liquid nitrogen and the surrounding air, a vacuum pressure is created in the mixing chamber causing an airflow from outside through the abrasive channels to the mixing chamber. By connecting the feedlines and an abrasive feeding system to the abrasive channels, an air-born abrasive feeding is realized. In the mixing process of the liquid nitrogen with the air and abrasive the jet loses its coherency, therefore a focusing tube is installed below the mixing chamber to form a coherent abrasive liquid nitrogen jet. The resulting diameter of the abrasive liquid nitrogen jet is nearly equal to the focusing tube diameter. The focusing tube is exposed to extremely abrasive conditions, therefore, it is made of a very wear resistant material.

V. Conclusion

In this paper, by using a computer simulation the applicability of cryogenic cutting technology was analyzed. In the computer simulation, a hybrid method that is combined with the SPH(smoothed particle hydrodynamics) method and the FE(finite element) method was used. And also a penetration depth equation for design of the cryogenic cutting system was derived to determine the design variables and operation conditions to cut a 10 mm thickness for steel. And the main components of the cryogenic cutting system were developed by using the obtained design values. The results of the study show that fluid jets by mixing liquid nitrogen and an abrasive at 300 m/s are possible to cut a 10 mm thickness for a steel plate. And also the design variables and operation conditions were established by using a penetration depth equation for the cryogenic cutting technology. Finally, the main components; intensifier, attenuator, pipe, and nozzle of the cryogenic cutting system were manufactured on the basis of the obtained design variables and operation conditions.

We have finished the design and manufacturing of the main components of the cryogenic cutting system, but we still have many problems to be solved. Especially, the evaporation of liquid nitrogen in the intensifier, attenuator, and pipes is one of the critical problems. Therefore, it is planned to develop cryogenic cooling systems for preventing the evaporation of liquid nitrogen.

It is expected that the cryogenic cutting technology will be a unique cutting solution for a hazardous environment, and if, this technology is developed, it might be in great demand in the nuclear industry as well as the aerospace, food, medical industry, etc..

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