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Experimental investigation of cutting performance for cast iron pipe in utility tunnel

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Abstract. The aging of utility tunnels is accelerating, and the deterioration of essential internal facilities, such as pipelines, is becoming a serious issue. Pipe cutting is essential for replacing aging pipes. However, no system exists for use inside utility tunnels. This study investigated the pipe-cutting performance of waterjet cutters, laser cutters, and diamond wire saws according to the standardized energy. A literature review was conducted to examine the cutting performance of cast iron based on the energy input of each cutting technology, and the findings were experimentally validated. Cutting tests on 20 mm ductile cast iron specimens revealed that a waterjet cutter required an effective kinetic energy of 60 J for a complete cut. For the laser cutter, a complete cut of 20 mm ductile cast iron was achieved at a laser power of 3,000 W, which is the primary performance variable. The diamond wire saw demonstrated limited applicability for cutting metallic materials, making it difficult to verify the cutting performance based on the energy input, so further experiments were deemed necessary. Finally, the minimum energy input required for 20 mm cast iron cutting has been determined. Moreover, the technical limitations and challenges associated with the practical application and optimization of each cutting technologies within utility tunnels were discussed. These findings provide fundamental data for evaluating the cast iron cutting performance of technologies, thereby contributing to the future development of equipment for cutting aging pipes.

Keywords: aging pipe-cutting; pipe cutting; utility tunnel; water pipe; waterjet cutter

1. Introduction

Utility tunnels are underground structures that efficiently integrate essential lifelines in urban areas (Luo *et al*. 2020, Valdenebro and Gimena 2018, Alaghbandrad and Hammad 2020). Utility tunnels have been constructed since the 19th century, with a primary focus on relocating utilities to underground spaces. Consequently, governance concerning aging mitigation and long-term maintenance was largely absent during this period (Canto-Perello and Curiel-Esparza 2013). Utility tunnels and internal facilities in many countries have reached the end of their service life (Gagnon *et al*. 2008, Ormsby 2009). Forman (2014) highlighted the severe deterioration of New York's infrastructure, noting undetectable underground water main failures beyond the capacity of engineers to identify. With increasing urbanization and underground space development, the demand for utility tunnels is expected to grow consistently (Wang *et al*. 2018). However, utility tunnels are aging rapidly (Fig. 1), and traditional management systems pose significant challenges for long-term maintenance (Lee *et al*. 2018).

As utility tunnels age, their integrated utilities also experience significant deterioration (Fig. 1). In particular, water mains inside utility tunnels have never been replaced since their installation because there are no specific replacement guidelines (Canto-Perello and Curiel-Esparza 2013). Aging water mains face critical declines in structural integrity and functionality, making them increasingly vulnerable to climate change effects (particularly freeze-thaw cycles and extreme rainfall) and human-induced events (An *et al*. 2024, Marrah *et al*. 2023, Jerez Lazo *et al*. 2024, Jiao *et al.* 2024, Yigit 2024, Zheng *et al*. 2024). The most severe consequence of aging water mains is the substantial financial loss due to leakage (Xuan *et al*. 2023). Larson and Sollo (1967) indicated that neglecting corrosion control in pipelines reduces water main capacity owing to continuous leakage. The deterioration of water pipes can result in more frequent leaks, higher maintenance and repair expenses, and negative impacts on water quality within supply systems. These failures can cause disruptions in water services and significant water and financial losses (Kim *et al*. 2006). Canadian municipalities reported that approximately 25% of the total 5 billion cubic meters of drinking water was lost annually owing to leaks and water

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(a) Utility tunnel

(b) Aging pipeline

Fig. 1 Aging utility tunnel and deteriorated pipeline within the tunnel (Park *et al*. 2024)

main failures across the country (Seica and Packer 2004). In Australia, corrosion in ferrous water mains within urban water distribution systems has made them increasingly more prone to failure (Petersen and Melchers 2012). Since 2000, the incidence of rust in tap water caused by aging water pipes in South Korea has been steadily increasing, resulting in a leakage rate of 14.1% and substantial economic losses (Kim and Sung 2003). Corrosion of aging pipes not only causes leaks but also poses direct risks to residents. As corrosion progresses, nodules formed by chemical reactions can reduce the cross-sectional area exposed to water, degrading the water quality and leading to rust-colored water. In severe cases, the erosion of the pipe material may reduce the pipe wall thickness, leading to a decline in water main strength and ultimately causing failures (Kelly 1986). External explosions or ruptures can trigger floods in operational environments, such as utility tunnels, which may lead to pipe bursts and casualties (Canto-Perello and Curiel-Esparza 2003). The aging of water mains is a critical issue requiring long-term replacement strategies rather than temporary repair (Mohebbi and Li 2011). However, pipe replacement systems specifically designed for utility tunnel environments do not exist.

1.1 A review of the applicability of pipe-cutting technologies within utility tunnel

This study focuses on pipe-cutting technologies suitable for utility tunnels. Pipe cutting is a prerequisite for future replacement projects, as individual pipes are joined using various methods, including mechanical, Tyton, and flange joints, depending on the pipe type. However, these joints corrode over extended use, making manual disassembly challenging (Wang *et al*. 2023). Developing specialized cutting equipment is essential to ensure efficient pipe replacement for long-term maintenance and system automation. Developing pipe-cutting tools for use inside utility tunnels requires further adaptation and advancement of existing cutting technologies. An appropriate system for pipe cutting depends on the material type, thickness, ambient environment, local safety and air quality codes, desired surface finish, and available financial resources (Blackburn 1994).

In conventional pipe-cutting operations, various systems and techniques are applied depending on the environment. Manual methods involve the operator performing the cutting directly, featuring a simple system with good portability and ease of use. However, their manual nature poses significant safety risks to operators and the surrounding environment. The confined workspace within utility tunnels forces operators into awkward postures and exposes them to close proximity to cutting tools, potentially leading to severe injuries (Canto-Perello and Curiel-Esparza 2003). Therefore, to apply the manual type within utility tunnels, comprehensive safety measures must be implemented to protect the operators and surrounding utilities. Several cutting technologies are available for manual pipe cutting. Traditionally, oxy-fuel cutters have been widely used, whereas tools such as blade saws, band saws, and laser cutters are used when a clean cut is required. Another cutting system involves clamping the cutting equipment around the pipe circumference. This approach can accommodate a wide range of cutting technologies, including chain-driven flame-cutting torches, abrasive wheels, grinders, laser cutters, and waterjet cutters. This method requires minimal operational space, making it suitable for confined spaces; however, it is not idealfor large-scale sites or environments requiring continuous cutting operations, such as utility tunnels. In addition, some systems hold pipes in place using hydraulic devices or lathes for cutting operations. These systems are primarily used in factories where automation and mass production of pipes are prioritized. However, because individual pipes must be manually clamped onto the cutting equipment, portability is limited, and their applicability in field operations is very low. Therefore, conventional pipe-cutting systems have limitations regarding safety, portability, and operability within utility tunnels.

As discussed earlier, it is challenging to apply conventional pipe-cutting systems in the physically narrow and elongated environments of utility tunnels. Therefore, an appropriate cutting technology must be proposed alongside a novel pipe-cutting system. One critical consideration is the cutting performance of the pipes. Most water mains within utility tunnels are currently operational; therefore, the water supply must be shut off or rerouted before cutting begins. In such cases, a rapid pipe-cutting process is essential because of the limited working time. In addition, financial losses can occur from pumping rerouted water back to restore normal operation. In long-term scenarios where several kilometers of pipeline need to be cut and replaced, cutting performance significantly influences both construction duration and overall cost. Hence, cutting performance is directly linked to the feasibility, efficiency, and financial aspects of the entire project. Furthermore, the cutting performance of the equipment is related to the size of the energy source; generally, larger energy sources yield better performance for the same cutting technology. Therefore, optimizing the equipment for confined spaces within utility tunnels requires careful consideration of cutting performance.

The performance and suitability of cutting technologies vary significantly depending on the target material, necessitating a thorough understanding of the materials used in aging pipes. Cast iron has been employed for water and sewage pipes since the late 19th century because of decreasing costs and improved durability (McGhee 1991). Initially, gray cast iron was predominantly used; however, technological advancements have led to its replacement with ductile cast iron (Petersen and Melchers 2012). Ductile cast iron offers advantages of tensile strength, elongation, and hardness owing to modifications in its chemical composition during casting.

Previous studies have analyzed cutting technologies suitable for steel and pipe cutting. Blackburn (1994) discussed advancements in pipe-cutting technologies, highlighting the emergence of techniques, such as plasma, laser, high-pressure waterjet, and cold cutting, alongside traditional oxy-fuel cutters. Notably, flame-cutting technologies, like plasma and laser cutters, offer the advantages of high cutting speed and superior cut quality. This study further explains that waterjet cutting technology can serve as an alternative to thermal cutting methods because of its ability to cut various materials without generating sparks or heat-affected zones (HAZ). Krajcarz (2014) examined the most suitable cutting technologies for metal cutting applications and recommended waterjet, laser, and plasma cutting as viable alternatives. In this study, a comprehensive performance comparison of three cutting technologies was conducted, focusing primarily on aspects such as cutting speed, quality, and applicability. Kafali *et al.* (2014) analyzed the most suitable cutting methods for steel in the shipbuilding industry, comparing thermal cutting methods (oxy-fuel and plasma cutting) and cold cutting methods (metal saw, band saw, and abrasive wheel cutting) based on performance categories. In addition, various other studies have investigated technologies suitable for steel cutting, consistently proposing waterjet cutting, laser cutting, and diamond wire saw technologies.

1.2 Goal of study

This study conducted a comparative analysis of the cutting performance of waterjet cutters, laser cutters, and diamond wire saws for ductile cast iron. Although previous studies have investigated the cutting performance of various cast iron types, none has generalized these findings for a comparative analysis based on material thickness. Therefore, this study aimed to generalize the cutting performance of ductile cast iron for each cutting technology based on a literature review and to determine the required cutting performance for pipes with a thickness of 20 mm.

The proposed model was cross-validated through actual experiments, and based on the experimental data, considerations, and limitations for the future application of cutting technologies within utility tunnels were analyzed. The results of this study provide a basic model for the cutting performance of ductile cast iron using selected cutting technologies, which can serve as foundational data for predicting the cutting performance for various cast iron thicknesses. In addition, a discussion on the applicability of each cutting technology in utility tunnels is expected to be used for future cutting equipment development.

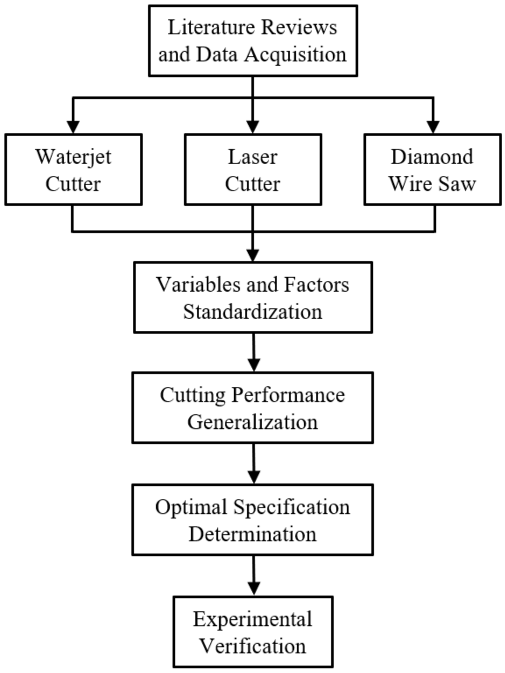


Fig. 2 Flowchart of the research procedure

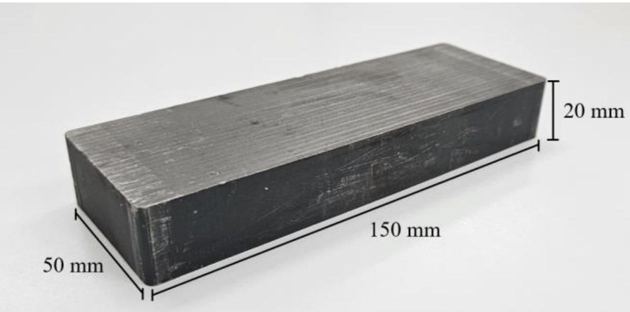
2. Experimental method

2.1 Research procedure

This study employed a methodology combining a literature review and validation experiments, as illustrated in Fig. 2. First, a literature review of prospective cast iron cutting technologies was conducted to determine the most suitable alternatives: waterjet cutters, laser cutters, and diamond wire saws. Experimental data were acquired from various studies, focusing on equipment specifications, experimental variables, material properties, and cutting performance indicators. Subsequently, the cutting energy and performance metrics were standardized to enable cross-

Table 1 Article review on waterjet cutting of cast iron

Author	Cutting system (Pump type)	Target material	Thickness (mm)	Pressure (MPa)	Traverse speed (mm/s)
Hashish (1989)	AWJ cutting (Intensifier)	Gray Cast Iron	≈ 20	170 - 340	2.5
Momber *et al*. (1996, 1997)	AWJ cutting (Intensifier)	Gray Cast Iron	50	140 - 345	4.2
Selvan *et al*. (2011)	AWJ cutting (Intensifier)	Gray Cast Iron	100	270 - 400	0.5 - 20
Selvan and Raju (2012)	AWJ cutting (Intensifier)	Gray Cast Iron	100	270 - 400	0.5 - 20
Kartal (2017)	AWJ cutting (Intensifier)	Ductile Cast Iron	20	150 - 350	1.67 - 5
Patil and Momin (2018)	AWJ cutting (Intensifier)	Carbidic Austempered Ductile Iron (CADI)	15	317	0.67 - 1



Tensile strength [MPa]	Bending strength [MPa]	Hardness [HB]	Elongation [%]	Specific gravity
500	610	200	10	7.15

Fig. 3 Physical properties of the ductile cast iron specimens used in the verification experiment

study comparisons. In the cutting performance generalization phase, a generalized model was developed based on the collected data to predict the cutting performance as a function of the energy input for each cutting tool. Finally, optimal specifications for application within utility tunnels were proposed and validated through empirical experiments.

2.2 Experimental material

Ductile cast iron, the most widely used material for water mains, was selected for the study; its detailed properties are shown in Fig. 3. The thickness of cast iron water mains varies based on the pipe diameter, pressure class, and joint type. According to ASTM A377-18, ductile iron pipes commonly used for water, wastewater, and fire protection have diameters ranging from 3” to 64” (76–1,625 mm), with thicknesses typically between 0.25” and 0.87” (6–22 mm). Therefore, the specimen thickness for the verification experiment was set to 20 mm, and each specimen was fabricated with 50 mm × 150 mm × 20 mm dimensions (Fig. 3).

3. Results

The cutting performances of waterjet cutters, laser cutters, and diamond-wire saws for cast iron were evaluated through a comprehensive literature review. However, variations in variables and performance indices across studies made direct comparisons difficult. To address this, energy input and performance metrics were standardized, enabling direct comparisons of the technologies. Subsequently, key performance-determining variables for each cutting method were analyzed, and the corresponding cutting performance was assessed. Finally, a generalized performance model was developed to define the required specifications for cutting aging cast iron pipes. The reliability of this model was confirmed through validation experiments.

3.1 Waterjet cutter

3.1.1 Review on cast iron cutting performance of waterjet cutter

This section presents a literature review to evaluate the cutting capability of waterjet cutters for cast iron. Waterjet cutting technology has been widely applied to various steels owing to its high versatility (Table 1). Hashish (1989) investigated the efficiency of abrasive waterjet cutting for metals. This study analyzed the effect of water pressure on cutting performance parameters (i.e., depth of cut, specific area generation, and maximum cutting traverse rate) based on experimental data. An intensifier pump operating at 170–340 MPa water pressure was used. Cutting tests were performed on materials such as gray cast iron, mild steel, titanium, and Inconel, with cutting depths ranging from 1.5

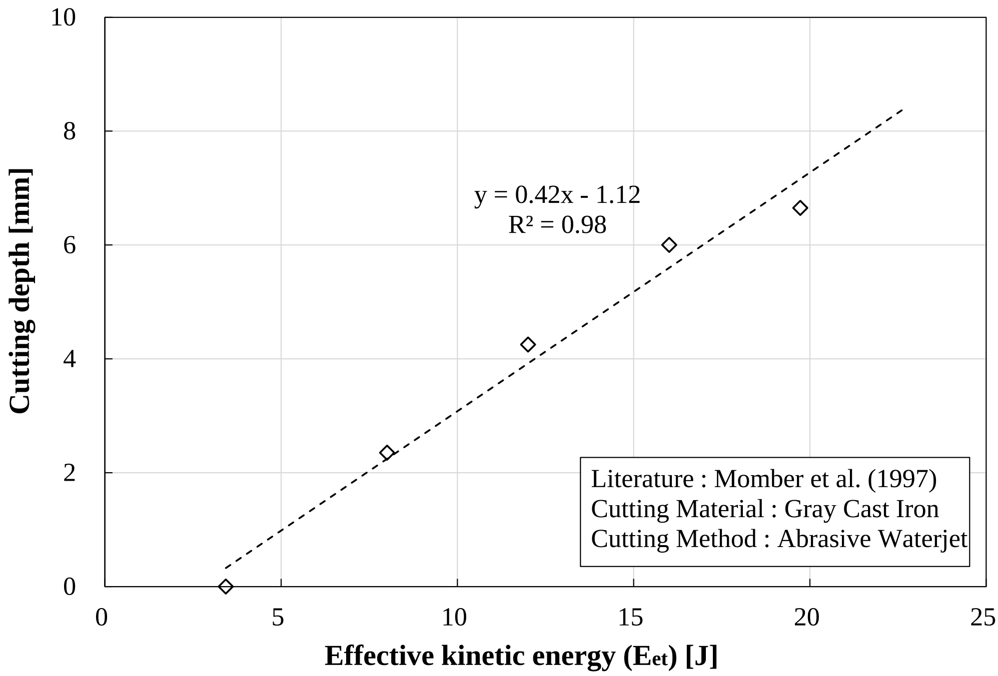


Fig. 4 Effective kinetic energy and corresponding cutting depth results from Momber *et al*. (1997)

mm to 16 mm, depending on the variables. Although the flow rate used in this study could not be verified, it was concluded that gray cast iron could be effectively cut with sufficient abrasive feed rate and pressure. Momber *et al.* (1996) analyzed the wear particles generated during waterjet cutting, focusing on grain size and size distribution. This study was later extended by proposing a material removal mechanism model based on an analysis of the removed wear particles (Momber *et al*. 1997). Experiments on 50 mm thick gray cast iron using an intensifier pump (140–345 MPa) showed material removal volumes between 85 and 245 mm^3. Selvan *et al.* (2011) investigated the effects of parameters on cutting depth in the abrasive waterjet cutting of cast iron. The objective of this study was to develop a predictive model for the waterjet cutting process applied to cast iron. They measured the cutting depth based on various parameters, including the abrasive flow rate, jet traverse rate, standoff distance, and focusing nozzle diameter. An intensifier pump capable of generating up to 4,000 bar of pressure was employed, with a pressure range of 270 to 400 MPa and a feed rate between 0.5 and 20 mm/s. Gray cast iron (100 mm thick) were used as the specimens. The experimental results showed that the cutting depth of the gray cast iron increased with higher pressures and lower feed rates, with depths ranging from 6 to 94 mm. In a follow-up study by Selvan and Raju (2012), the same experimental parameters were used to investigate the surface roughness of cast iron during waterjet cutting. Kartal (2017) examined kerf taper minimization in waterjet machining. The experiments involved adjusting the water pressure and traverse speed to cut 20 mm of ductile cast iron and subsequently measuring the kerf geometry. The analysis focused on the kerf geometry and investigated the most dominant operating parameters influencing kerf formation. Patil and Momin (2018) conducted a parametric analysis of the material removal rate of carbidic austempered ductile iron (CADI) in waterjet machining. An intensifier pump capable of generating a maximum pressure of 380 MPa and maximum flow rate of 3.81 L/min was used. The cutting material was 15 mm thick CADI, and the material removal rate was used as the performance index. A review of existing literature indicates that waterjet cutting performance for cast iron using waterjet technology has been analyzed using various parameters. However, differences in waterjet energy parameters and performance indices across studies make direct comparisons challenging. Therefore, a standardized analysis of waterjet energy and performance indices across studies is necessary for a concise comparative evaluation.

3.1.2 Standardization and generalization of waterjet cutter performance in cast iron cutting

Various interconnected variables influence the performance of waterjet cutting technology. Several studies have focused on optimizing and modeling waterjet energy by analyzing these factors (Oh and Cho 2016, Janković *et al.* 2018). The process of cutting a target material with abrasive water jets involves erosion caused by abrasive particles accelerated by a high-velocity water stream (Oh and Cho 2014). Therefore, understanding the energy of abrasive particles in relation to different variables is crucial for predicting waterjet performance. Oh and Cho (2016) proposed a formula for calculating the kinetic energy of abrasive waterjets based on influential variables (e.g., energy, geometry, material, and nozzle system parameters) and analyzed the correlation between the kinetic energy and cutting depth of the target material. Their findings revealed that the kinetic energy of abrasive water jets is primarily

Table 2 Experimental parameters of abrasive waterjet (AWJ) cutting acquired from previous studies

Parameter	Water pressure [MPa]	Traverse speed [mm/s]	Standoff distance [mm]	Abrasive feed rate [g/s]	Water flow rate [g/s]	Orifice diameter [mm]	Abrasive type [-]	Abrasive size [-]
Momber *et al.* (1997)	140 - 345	4.2	9	4.3	4.3	0.33	Garnet	# 36
Selvan and Raju (2012)	270 - 400	0.5 - 20	1.85 - 5	8 - 15	40	0.35	Garnet	# 80

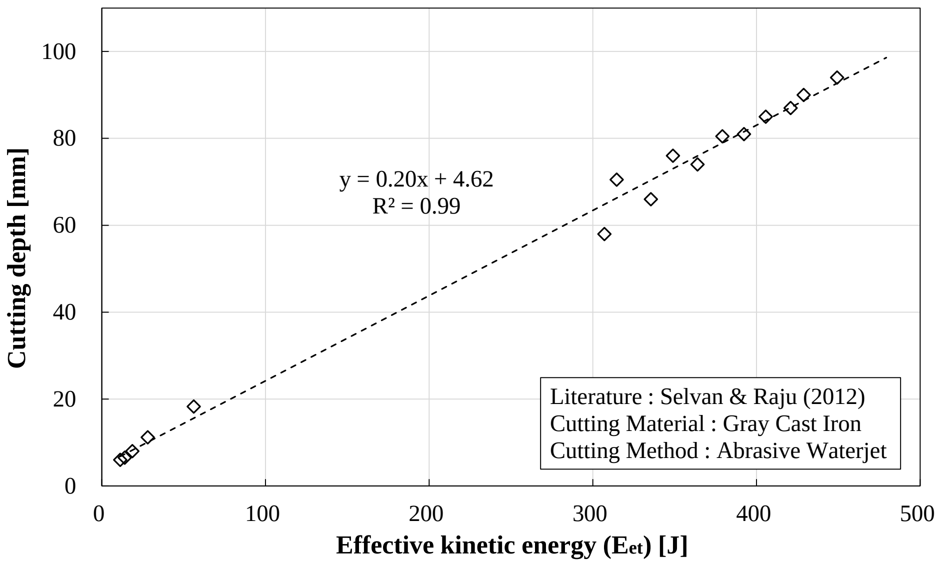


Fig. 5 Effective kinetic energy and corresponding cutting depth results from Selvan and Raju (2012)

determined by water velocity and pressure, whereas the cutting depth depends on the properties of the target material. This study derived effective kinetic energy from the kinetic energy formula of a high-speed jet stream and standardized the jet energy. The effective kinetic energy represents the kinetic energy at the point of jet discharge from the nozzle and is expressed as a function of abrasive feed rate, abrasive mixing ratio, pump pressure (water velocity), flow rate, orifice diameter, and nozzle traverse speed Eq. (1). This equation theoretically indicates the energy generated at the nozzle, independent of the target material, and was later verified through experimental data.

In this analysis, the existing literature data were standardized using the formula below, and the resulting cutting performance for cast iron was observed.

$$E_{et} = \frac{1}{2}\dot{m}_a[\frac{C_e \cdot C_k}{1 + (\dot{m}_a/\dot{m}_w)}]^2 \frac{d_0}{s_n} \cdot p_{wp} \quad (1)$$

Where,
E_{et} = Effective kinetic energy (J)
$\dot{m}_a$ = Abrasive mass per unit time (kg/s)
$\dot{m}_w$ = Water mass per unit time (kg/s)
C_e = Mixing efficiency coefficient in inelastic collision theory (-)
C_k = Coefficient in the relationship between water velocity and water pressure $[m^2/(s \cdot \sqrt{kg})]$
d_0 = Orifice nozzle diameter (mm)
s_n = Traverse speed of nozzle (mm/s)
p_{wp} = Water pressure in the pump section (kg/m^2)

Table 2 summarizes the valid values from reviewed studies, excluding those with unavailable or duplicate parameters.

Subsequently, the experimental parameters from each study were substituted into Eq. (1), and the calculated energy values were compared with the corresponding outcomes. Fig. 4 illustrates the effective kinetic energy and corresponding cutting depth calculated based on the data acquired from Momber *et al*. (1997). In this study, cutting depth was used as the performance index, with measured depths ranging from 2 to 7 mm under pressure conditions of 140 to 345 MPa. The pressure was the only adjusted variable in the experiment; therefore, a linear relationship between the pressure variable and E_{et} was observed according to Eq. (1). The literature indicated that when other variables were held constant, a 60 MPa pressure was the threshold below which no material cutting occurred.

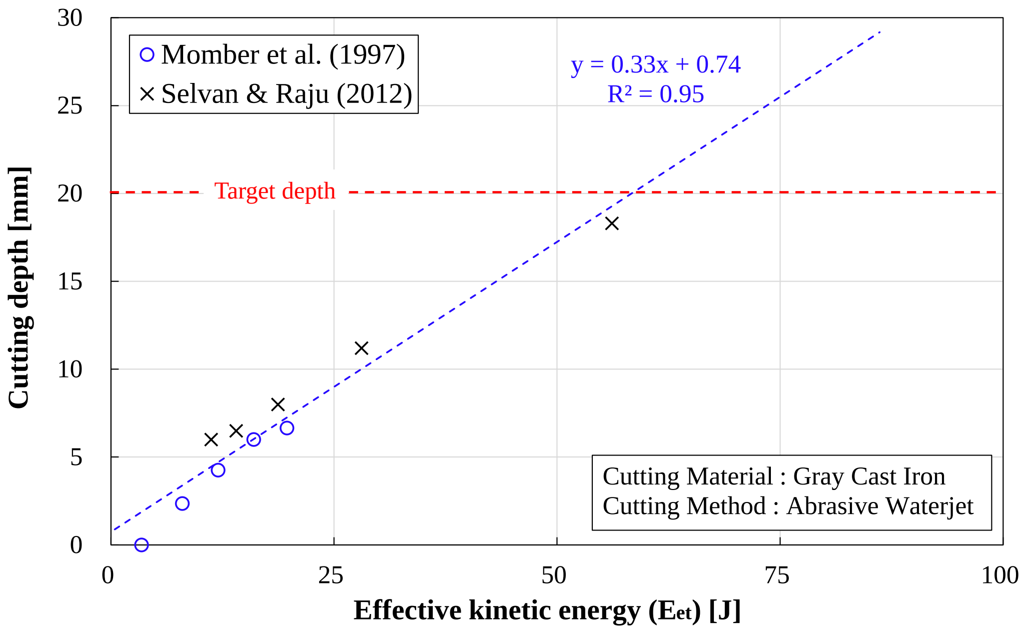


Fig. 6 Effective kinetic energy requirement for waterjet cutting of aging pipes

When this threshold value was converted to E_{et}, it corresponded to approximately 5 J.

Selvan and Raju (2012) conducted cast iron cutting experiments by adjusting various parameters, including pressure, and using cutting depth as the performance metric. The measured cutting depths ranged from 6 to 94 mm (Fig. 5). In the experiments, five cases were analyzed by varying the traverse speed at 4, 8, 12, 16, and 20 mm/s to observe the trends. For the remaining tests, the traverse speed was set at 0.5 mm/s, yielding higher cutting depths. The effective kinetic energy, E_{et} was calculated for each parameter, with values ranging from 10 to 450 J.

Fig. 6 presents the integrated cutting depth results as a function of E_{et}, based on experimental data from previous analyses, focusing on data with E_{et} values below 100 J, considering the target cutting depth scale. A target cutting depth of 20 mm thickness, common for water mains within the typical pipe diameter range (ASTM 2022), was used. According to the generalized model in Fig. 6, an E_{et} of at least 60 J is required to cut 20 mm of gray cast iron. This value was derived theoretically and requires further experimental validation to enhance its reliability. The design parameters for the validation experiment were set at a target performance of 60 J based on the analysis in Fig. 6.

3.1.3 Experimental verification of waterjet cutting performance

Fig. 6 presents a generalized model of the gray cast iron cutting capacity of an abrasive waterjet (AWJ) system based on E_{et}. The E_{et} values were calculated using Eq. (1), indicating that at least 60 J of energy is required to cut through 20 mm of gray cast iron. To cross-verify the model, an experiment was conducted to cut a 20 mm ductile cast iron using the specified E_{et} value. First, the experimental parameters required to achieve an effective kinetic energy of 60 J were investigated. Fig. 7 illustrates the calculated E_{et} of the waterjet as a function of traverse speed and water pressure based on Eq. (1). The remaining parameters were set according to the experimental equipment settings. As shown in Fig. 7, the values needed to achieve an effective energy of 60 J were identified. According to the model, when the waterjet pump pressure is set to 200, 300, and 350 MPa, the corresponding traverse speeds required to achieve E_{et} of 60 J are 0.75, 1.5, and 1.75 mm/s, respectively.

In the verification experiment, the variables were set based on the derived values, with the final experimental design parameters shown in Fig. 8. Water pressure was fixed with the value of 350 MPa, and the traverse speed was adjusted between 0.8 mm/s to 3.3 mm/s to attain the target energy. The specimen was fixed in the worktable and 30 mm of cutting operations was conducted for each cutting speed. The waterjet system comprised an intensifier-type pump, a pneumatic device for consistent abrasive feeding, a water chiller, and a water tank. The pump had a power rating of 30 hp and provided a flow rate of 3.18 l/min with an orifice diameter of 0.3 mm. The maximum generated pressure was 4,150 bar, and the maximum operating pressure was 3800 bar. The experimental parameters included pressure of 350 MPa and traverse speeds of 0.8, 1.67, 2.5, and 3.3 mm/s.

Fig. 9 shows the results of the verification experiment for cutting ductile cast iron using a waterjet at varying traverse speeds. At 3.3 mm/s, the waterjet could not achieve a complete cut and reached an average depth of 16 mm. At a speed of 2.5 mm/s, the waterjet performed a partial complete cut, averaging 19.5 mm cutting depth. When the traverse speeds were reduced to 1.67 and 0.8 mm/s, the waterjet fully penetrated the 20 mm ductile cast iron specimen, suggesting that the actual cutting depth exceeded the thickness of the specimen (20 mm).

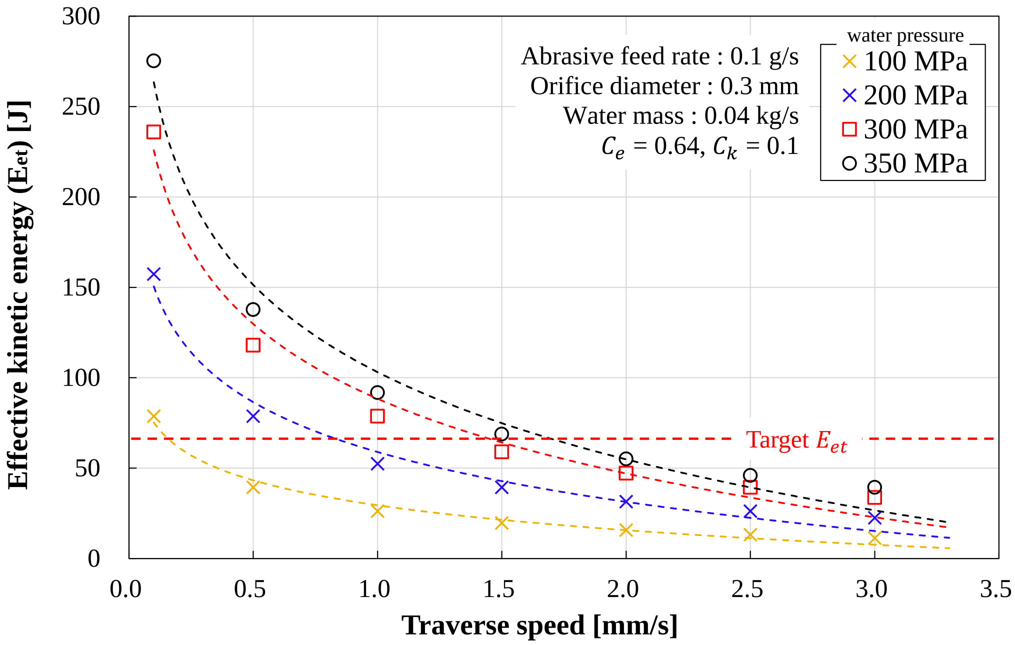


Fig. 7 Effective kinetic energy according to the traverse speed and water pressure

Water pressure [MPa]	Traverse speed [mm/s]	Abrasive flow rate [kg/s]	Water flow rate [L/min]
350	0.8 1.67 2.5 3.3	0.01	2.66

Fig. 8 Waterjet cutter and parameters used in the verification experiments

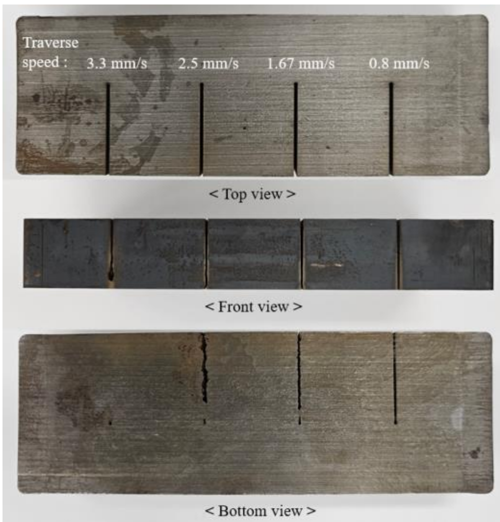


Fig. 9 Results of the waterjet cutting verification experiment.

In Fig. 10, the cutting-depth results of the verification experiments and the corresponding E_{et} values are applied to the generalized model suggested in Fig. 6. The E_{et} values were calculated as 41.7, 55.1, 82.4, and 172 J for traverse speeds of 3.3, 2.5, 1.67, and 0.8 mm/s, respectively, with measured cutting depths of 16, 19.5, 20, and 20 mm. The experimental results showed discrepancies of 10% and 3% for E_{et} values of 41.7 J and 55.1 J, respectively, both within a 10% deviation. For the cases with traverse speeds of 1.67 mm/s and 0.8 mm/s, the cutting depth was recorded as 20 mm, which corresponds to the specimen thickness, suggesting that the actual cutting depth exceeded 20 mm. The generalized model was cross-verified based on these results, and fundamental data on ductile cast iron cutting using waterjet technology were acquired. These findings serve as crucial reference materials for determining pump specifications and power ratings in the detailed design of cutting equipment for aging pipe.

3.2 Laser cutter

3.2.1 Review on cast iron cutting performance of laser cutter

Laser cutting utilizes a high-temperature laser beam, demonstrating exceptional performance in steel cutting. Table 3 summarizes findings from studies on laser cutting cast iron.

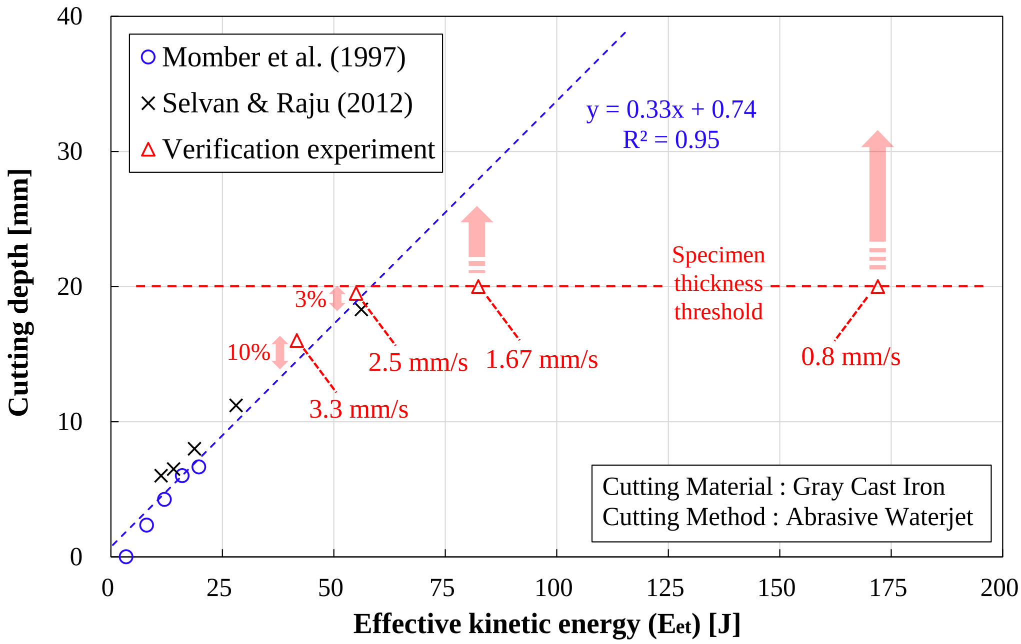


Fig. 10 Correlation between the effective kinetic energy and cast iron cutting depth based on the experimental results

Table 3 Article review on laser cutting of cast iron

Author	Laser type	Target material	Assist gas type	Laser power (W)	Cutting speed (mm/s)
Masood *et al.* (2011)	Nd:YAG Laser	White Cast Iron	Mechanical tool	800 - 1500	-
Meško *et al.* (2017)	CO_2 Laser	Ductile Cast Iron	O_2 , N_2	3200 - 4000	5.3 - 26.67
Nenad *et al.* (2020)	CO_2 Laser	Ductile Cast Iron	O_2 , N_2	3200 - 4000	5.3 - 26.67
Khaleel (2023)	Numerical Analysis	Gray Cast Iron	-	200 - 600	-

Masood *et al.* (2011) proposed an alternative method for processing hard-to-wear materials using a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser. The target material, high chromium white cast iron (HCWCI), is a chemically modified material of standard cast iron designed to enhance wear resistance. Specimens were mounted on a lathe for as selecting the correct laser power. Nenad *et al.* (2020) further investigated cutting speed effects using the same variables. They observed that reducing the cutting speed improved laser beam penetration and surface quality of the ductile cast iron. Regarding the assist gas, a mixture of 70% O_2 and 30% N_2 produced the cleanest cut surface. Although O_2 gas enabled higher cutting speeds, it risked the formation of welded joints or dendritic oxide structures, making the choice of gas type critical depending on specific operational goals. Khaleel (2023) conducted a systematic analysis of the effects of laser power on strain distribution in gray cast iron using numerical simulations of laser cutting. The mesh was designed using the ANSYS 2020 software, incorporating the mechanical properties of gray cast iron. The workpiece was then subjected to a simulated laser power range of 200 to 600 watts. The results indicated surface deformations of 0.2 to 0.5 mm on gray cast iron, depending on the laser power applied. As these results were based on simulations, further validation with experimental data is needed for reliability.

3.2.2 Standardization and generalization of laser cutter performance on cast iron cutting

Laser cutting performance depends on various factors, including laser power, focusing lens diameter, laser wavelength, assist gas type, gas pressure, and nozzle tip diameter. Numerous studies have attempted to generalize the amount of laser energy and predict the cutting performance of materials considering these complex factors. However, different types of lasers (such as Nd:YAG, CO_2, and O_2 Lasers) are specialized for specific applications, and the parameters interact with one another, making it challenging to model the energy input based on the variables (Hühnlein *et al.* 2010). In laser cutting, key

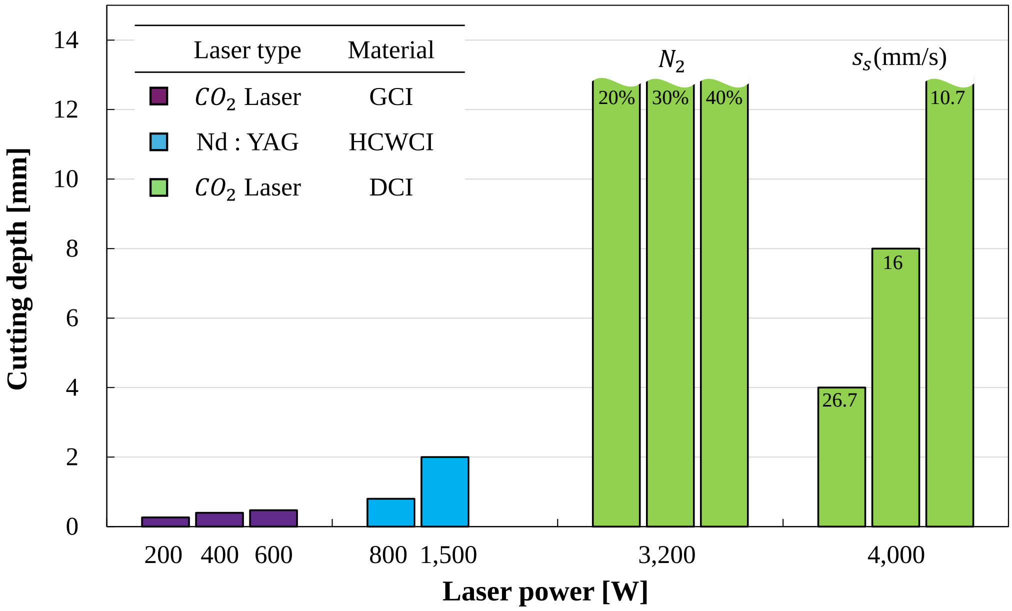


Fig. 11 Laser cutting capacity based on operational parameters

variables affecting cutting performance are laser power, cutting speed, and assist gas (Madić *et al.* 2020). For smooth cutting operations, the laser must effectively melt the material while following the cutting path, which requires an optimized cutting speed based on laser power. In addition, laser power and cutting speed determine the size of the key equipment components, such as the energy source and chiller. Therefore, laser power is considered the most critical factor for equipment design and a key performance indicator for laser cutting, making it the primary comparison metric in this analysis.

Predicting precise laser cutting performance is complex because of issues such as re-joining (where melted material cools and re-bonds, preventing complete separation) and partial penetration (asymmetric cutting where only certain sections are penetrated), which vary depending on the assist gas type used (Meško *et al.* 2017). Laser cutting is commonly employed in precision machining industries, where the most critical performance indicator is the kerf or cut width. A narrower kerf indicates higher precision. In addition to kerf, other performance metrics such as material removal rate (MRR), heat-affected zone (HAZ), and surface roughness are used to evaluate cutting performance and efficiency (Madić *et al.* 2020). However, because the objective of this study was to explore the cutting feasibility of aged pipes with specific thicknesses, precision machining, and smooth surface cuts were not the primary considerations. Therefore, the analysis focused on the cutting depth as the key performance index.

Based on the literature review summarized in Table 3, the laser cutting experimental parameters and corresponding cutting depth results were obtained (Fig. 11). For gray cast iron, the cutting depths at laser powers of 200, 400, and 600 W were 0.27, 0.4, and 0.47 mm, respectively. Although the cutting performance improved slightly with increasing laser power, the overall trend was minimal. Using an Nd:YAG laser on high chromium white cast iron (HCWCI), the cutting depths at 800 and 1500 W were 0.8 mm and 2.0 mm, respectively. Despite increased cutting performance at higher laser power, these results did not meet target requirements. The green graph in Fig. 11 shows the cutting results for ductile cast iron obtained using a CO_2 laser. The O_2 gas was the primary assist gas, and experiments were conducted at 3,200 W laser power with the addition of N_2 gas at concentrations of 20%, 30%, and 40%.

The results showed that complete cutting of the 13 mm specimens was achieved when N_2 was added, with very clean-cut surfaces. At 4,000 W laser power, the scan speeds were set to 10.7, 16, and 26.7 mm/s as control variables. The resulting cutting depths were 13 mm, 8 mm, and 4 mm, respectively. These results confirmed that with optimized parameters at laser powers of 3,200 W or higher, ductile cast iron can be cut to depths ranging from 6 to 13 mm. Furthermore, the study found that laser cutting performance does not increase linearly with enhanced laser power and scanning speed; rather, it requires appropriate settings of other parameters, such as assist gas and scan speed, to achieve optimal results. However, this review highlighted inconsistencies in laser types and target materials, and the cutting performance for ductile cast iron thicknesses above 20 mm has not been verified, indicating the need for additional validation experiments. Based on the analysis in Fig. 11, the recommended performance requirements for cutting 20 mm ductile cast iron are a laser power of at least 3,000 W and a traverse speed <10 mm/s, which were incorporated into the experimental design parameters.

3.2.3 Experimental verification of laser cutting performance

A laser cutting machine comprises a laser energy source, laser head, working table, and chiller. The energy source used in this system was an ytterbium fiber laser with a

Laser power [W]	Traverse speed [mm/s]	Assist gas type
3000	4.2	
4000	5.8	O_2
5000	7.7	

Fig. 12 Laser cutter and parameter used in the verification experiments

maximum output power of 12 kW (Fig. 12). The verification experimental variables were determined based on an analysis of the laser cutting performance (Fig. 11). The experiments were conducted at power levels of 3,000, 4,000, and 5,000 W, with the corresponding cutting speeds set to 4.2, 5.8, and 7.7 mm/s, respectively. The specimen was fixed upon the worktable and 50 mm of complete cutting was conducted for each test cases. The cutting speeds were optimized to match the energy output, as deviating from the specified speed—either slower or faster—significantly reduced cutting performance. Oxygen was chosen as the assist gas, with the gas pressure set at 1 bar.

The results showed that complete cutting of the 20 mm ductile cast iron specimens was achieved in all three cases (Fig. 13(a)-13(c)). The top cutting surfaces in each case were clean. However, the bottom cutting surfaces had wider kerfs and were less smooth owing to the nature of laser cutting, where the molten material is blown through the opposite side. In particular, Fig. 13(c) shows oxide formation on the bottom surface, identified as spheroidal graphite formed by the chemical reaction between O_2 gas and cast iron. Although this could potentially affect cut quality, it did not hinder achieving the target cutting depth. These results confirmed the feasibility of cutting 20 mm ductile cast iron using laser powers of 3,000 to 5,000 W with O_2 assist gas. In addition, it was found that the cutting performance did not increase linearly with higher laser power and cutting speed; instead, optimized operating parameters specific to material type and thickness were necessary.

3.3 Diamond wire saw cutter

3.3.1 Review on cast iron cutting performance of diamond wire saw cutter

The use of diamond wire saws for cutting metals is relatively rare. In industry, diamond wire saws are primarily used for stone cutting and are generally not recommended for dense materials like metals, except in specific circumstances. In addition, diamond-wire sawing is considered inefficient for steel materials because of the chemical affinity between diamond and iron (Wilks and Wilks 1991). However, advancements in tool configuration and optimization have allowed their application in steel cutting to emerge (Jennings 1995). Tönshoff and Hillmann (2002) described the interaction between diamond wire saw and metalwork pieces (Table 4). Their study presented the cutting capacity of diamond wire saws on aluminum, ferritic steel, and austenitic steel. The working pressure of the hydraulic motor was set to 2.4 MPa, and the cutting capacity (mm^2) was used as the performance index. While they demonstrated the feasibility of cutting metal materials with diamond wire sawing, detailed operational parameters for cast iron were not provided, and its cutting performance remains unclear, necessitating further investigation. Tantussi *et al*. (2005) reported experimental results on the diamond wire cutting of cast iron, focusing on the geometry of diamond beads. The study compared the performance of cylindrical and tapered electroplated diamond beads under cutting forces ranging from 4.8 to 11.9 N. Cutting performance was evaluated based on the periodically measured material removal volume (mm^3). A literature review on diamond wire sawing of cast iron revealed limited information on specific parameters and diverse performance indices, making direct comparisons difficult. Therefore, additional validation experiments are required to determine the performance of the target material.

3.3.2 Standardization and generalization of diamond wire saw cutter performance in cast iron cutting

The cutting mechanism of a diamond wire involves the frictional action of individual diamond beads against the target material. In the first stage, the contact surface between the diamond beads and the target material increases, generating heat at the contact point, which leads to elastic deformation of the material. In the second stage, the target material underwent both elastic and plastic deformation as the force exerted by the diamond beads increased. In the final stage, the material experiences the greatest deformation, leading to chipping and cutting of the material (Tönshoff and Hillmann 2002).

Previous studies have explored optimizing the cutting energy of diamond wire sawing by considering various influencing factors (Liu *et al*. 2017, Wang *et al*. 2017, Qiu *et al*. 2020). The cutting performance of diamond wire saws depends on a complex interplay of factors, and extensive research has focused on the controllable parameters. Amirsharafi *et al*. (2023) reviewed the controllable parameters of diamond wire saws and reported that wire peripheral speed and pullback force significantly affect performance. The most common evaluation criteria were efficiency and cutting rate, with some cases evaluated based on the material removal rate. Additional factors include normal force applied by the saw, cutting speed, bead configuration, and operating methods (Clark *et al*. 2003).

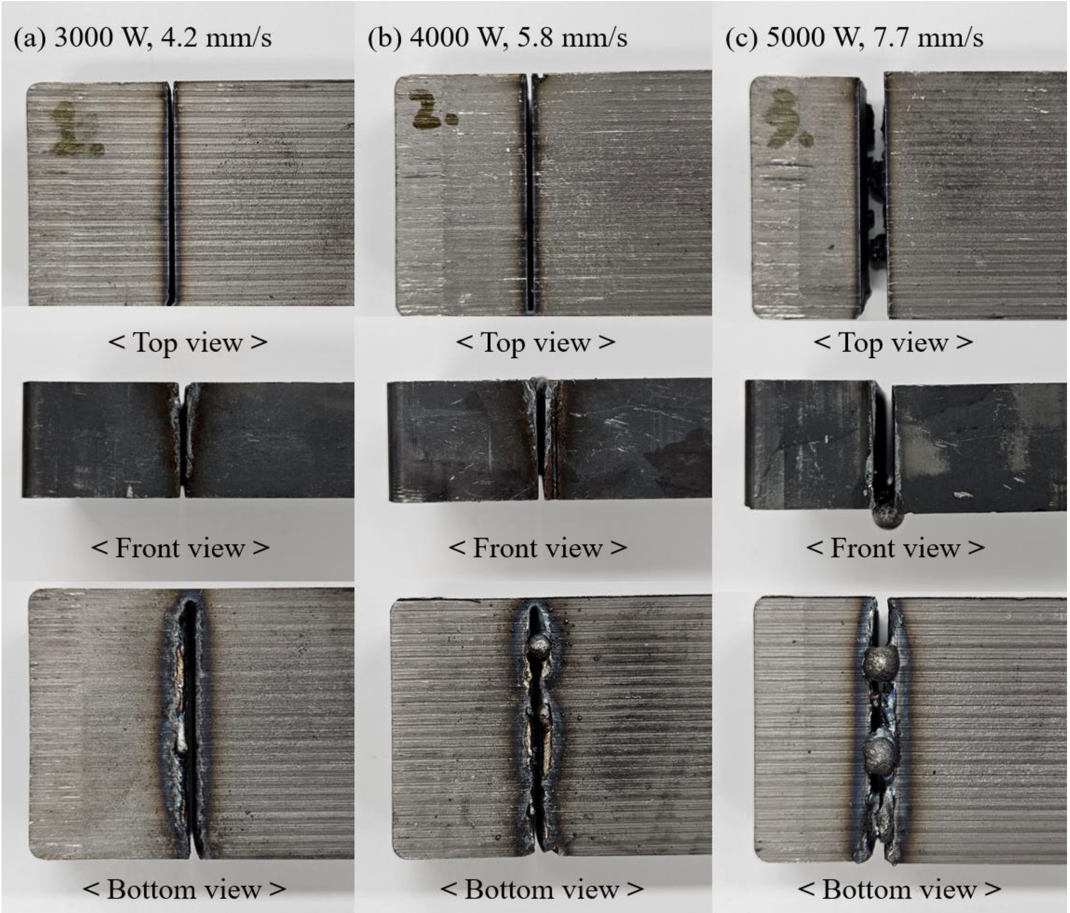


Fig. 13 Results of the laser cutting verification experiment

Table 4 Article review on diamond wire saw cutting of metal materials

Author	Diamond bead type	Target material	Thickness (mm)	Cutting force (MPa)	Cutting speed (m/s)
Tönshoff and Hillmann (2002)	Electroplated	Metal material	-	2.4	**22.3**
Tantussi *et al.* (2005)	Electroplated	Cast Iron	5	4.8 - 11.9	19 - 26

Since diamond wire saws are cut by maintaining a contact line along the cutting section and slicing the material from both ends, using cutting depth as a performance metric seems inadequate. Moreover, most studies focused on stone cutting, limiting the applicability of existing models to cast iron. Therefore, cutting aged pipes with diamond wire saws requires specially designed experiments.

3.3.3 Experimental verification of diamond wire saw cutting performance

In the verification experiment, the diamond wire saw was used as a pneumatic tension system. The wire was driven in a reciprocating motion by a motor, cutting the specimen under air pressure generated by a pneumatic pump. The equipment supports wire diameters from 0.25 to 0.42 mm, spooler spin speeds from 2 to 260 RPM, and air pressure between 0.1 and 0.5 MPa. Owing to limited research on cutting ductile cast iron using diamond wire saws, determining the optimal cutting conditions remains challenging. In this experiment, a motor generating 3 amps,

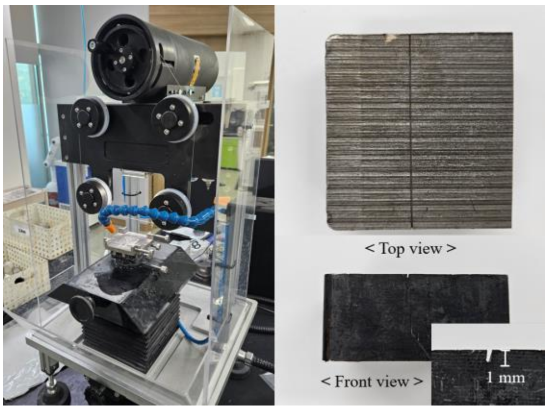


Fig. 14 Diamond wire cutting machine and verification experimental results

Table 5 Results of the analysis on optimization of cutting technologies within the utility tunnel

Criterion	Waterjet cutter	Laser cutter	Diamond Wire Saw
Standardized energy requirement for 20 mm ductile cast iron cut	Effective kinetic energy of 60 J	Laser power of 3000 W	-
Cutting speed	1 ~ 2.5 mm/s	4 mm/s	-
Pros	▪ High versatility due to the non-contact trait. ▪ Low risk of fire.	▪ Fast cutting speed on ductile cast iron.	▪ Can cut wide range of materials.
Cons	▪ Scattering of debris and fragments to other facilities and operator. ▪ Malfunction of system due to the complexity.	▪ Hazardous fumes and gases must be controlled. ▪ Frequent parametric optimization needed.	▪ Fast rotational motion and high-tension wire may have a risk of physical harm. ▪ Low persistence.

1.8 Nm torque, and 200 W power was used. The RPM was set at 100, and cutting tests were performed on 20 mm ductile cast iron specimens (Fig. 14). After 10 min of reciprocating operation, a cutting depth of 1 mm was observed. The experimental results indicate that a diamond wire saw driven by a 200 W motor is insufficient for cutting ductile cast iron, highlighting the need for further investigation.

4. Discussion

In optimizing cutting technologies for aging pipes in utility tunnels, performance requirements were proposed and validated experimentally (Table 5). Non-contact cutting technologies, such as waterjet and laser cutting, demonstrated high applicability for ductile cast iron. In experiments targeting 20 mm thick ductile cast iron, waterjet cutting technology used effective kinetic energy as the evaluation metric, requiring 60 J for a complete cut. The verification experiment involved adjusting variables such as the waterjet pressure (set at 350 MPa) and traverse speed to generate 60 J of energy, successfully verifying the feasibility of cutting the specimen. Alternative methods for achieving the target effective kinetic energy include modifying water pressure and abrasive feed rate. Thus, further research should focus on adjusting other parameters, such as water pressure, to identify the cutting threshold for ductile cast iron. For laser cutting, laser power was used as an evaluation metric for comparative analysis. The feasibility of cutting ductile cast iron was confirmed at laser power levels between 3,000 and 4,000 W, and the experimental variables were set accordingly. In the experiments, the complete cutting of 20 mm thick ductile cast iron was achieved at laser power settings of 3,000, 4,000, and 5,000 W. Research on diamond wire saws for cutting cast iron remains limited. High wear at contact points when cutting hard materials and reduced applicability for continuous operation are the primary limitations of mechanical cutting techniques. In addition, industrial diamond wire saws are designed for either large-scale stone cutting or precision machining of brittle materials, limiting their suitability for use in confined spaces within utility tunnels (2 m x 3 m). Compact equipment capable of sufficient cutting performance for cast iron in such spaces requires further development.

During the validation experiments, potential technical limitations that could arise when applying cutting technologies to utility tunnels were also explored. To apply waterjet equipment, measures are required to address the splashback of water and abrasive particles. Adequate safety mechanisms must be implemented to prevent harm to operators and surrounding facilities. In addition, frequent malfunctions of the intensifier pump are anticipated. In a waterjet system, the intensifier pump generates pressure through a series of complex mechanical conversions. Frequent adjustments in field operations can strain the machinery and pumps. Therefore, it is crucial to adhere to appropriate operational practices for various parameters during design. Several technical aspects must be considered when applying laser equipment to cut aged pipes in utility tunnels. Optimizing the cutting speed according to the laser power is a critical task; failure to do so may result in ineffective cutting and laser reflections, which may damage the equipment. Furthermore, the optimal parameters must be manipulated for each target material. The generation of toxic fumes and harmful gases during cutting must be addressed, particularly in confined spaces. Finally, the limitations of using diamond wire saws were analyzed. Diamond wire sawing requires generating cutting tension through very long wires, making them prone to breakage or damage. Weak cutting force or tension hinders cutting efficiency, whereas excessive tension risks wire breakage, causing interruptions in the cutting process. Depending on the industry and equipment used, wires can range from at least 10 m to over 100 m in length, and any damage can incur significant economic and time losses.

Additionally, meticulous investigations towards the utility tunnels environments and structures are essential for optimization of pipe-cutting system. For instance, if the internal free space in particular site is too confined to accommodate the entire system, certain components must be positioned externally (e.g., water pump and laser energy source). In following case, significant pressure loss could occur in application of waterjet system due to the extension of water hose. Similarly, in application of laser cutting system, operational cost could increase significantly when optical cable is prolonged. Accordingly, structural inspections of individual utility tunnel sites, including the internal free space and the spacing of the material entry ports are crucial for further optimization. It is also important to understand policies related to safety and environmental considerations for operation within utility tunnels. It is necessary to verify whether the used water and abrasives generated during waterjet cutting qualify as industrial waste, in order to establish a proper disposal plan. Moreover, fumes and gases produced during the cutting operation must not exceed the air pollution standards within the utility tunnel. These technical issues should be critically considered in the detailed design of the equipment and its industrial applications.

5. Conclusions

This study examined cutting technologies suitable for aging pipe cutting in confined spaces within utility tunnels. Cutting technologies were selected based on a literature review, and the cutting performance of cast iron, which is the most commonly used material in aged pipes, was evaluated. Subsequent validation experiments assessed the cutting performance of 20 mm ductile cast iron, and the challenges to be addressed for industrial applications were reviewed. The main findings are as follows.

- The cutting performances of waterjet cutters, laser cutters, and diamond wire saws for cast iron were reviewed. Waterjet cutting is widely applied in the metal processing industry and can cut cast iron of various thicknesses under pressures >300 MPa. Laser cutting also demonstrated strong cutting performance for cast iron, being able to cut ductile cast iron with thicknesses >13 mm at laser power levels of 3,000 to 4,000 W. However, the applicability of diamond wire saws for cast iron cutting is low, and relevant prior research is limited.
- To enable a direct comparison of waterjet cutting performance, the energy input was standardized, and a generalized model for cutting cast iron was proposed. The energy input of the waterjet was standardized using effective kinetic energy, and the expected cutting depth of the cast iron was estimated based on this value. The prediction model estimated an E_{et} value of 60 J for cutting 20 mm cast iron. This model was verified with a deviation of less than 10% through experimental data and is expected to serve as a foundational model for predicting cast iron cutting performance using waterjet technology in future applications.
- In cutting ductile cast iron using a CO_2 laser, cutting depths exceeding 13 mm were achieved under laser powers of 3,000 to 4,000 W and assist gases, O_2 and N_2. Subsequent validation experiments confirmed the feasibility of complete cutting of 20 mm thick ductile cast iron at laser power levels of 3,000, 4,000, and 5,000 W using O_2 as the assist gas. However, the cutting quality on the contralateral side was suboptimal.
- Diamond wire saws were unsuitable for cutting aged pipes within utility tunnels. Owing to the nature of the contact-cutting traits, the equipment experiences significant wear, resulting in low operational durability and limited applicability across different environments.
- Cutting experiments for each technology were conducted on ductile cast iron, and the limitations that must be addressed for field applications were analyzed. The waterjet cutter demonstrated excellent performance regarding cutting depth and speed, showing the highest applicability. However, safety measures for handling airborne particles and debris must be implemented during field use. The cutting performance of a laser cutter depends significantly on optimized operational parameters. Performance does not increase linearly with energy input; instead, detailed parameter adjustments based on the physical and chemical properties of the material are essential. The diamond wire saw exhibited low applicability for cutting cast iron. Issues related to wire damage, such as safety and economic costs, must be addressed.

Non-contact cutting equipment, such as waterjet and laser cutters, are highly applicable for cutting aging pipes within utility tunnels. However, the limitation of this study lies in its inability to consider the effects of individual operational variables on the cast iron cutting performance but only focused on the standardized energy. For detailed design of cutting equipment, the specific characteristics of utility tunnels and specific design elements must be considered for the further optimization of each cutting technologies. Moreover, additional studies should focus on conducting cast iron cutting experiments with a wider range of operational parameters and accumulating more data to enhance the reliability and development of the proposed model.

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