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WELDING ROOM DEVELOPMENT FOR SIMULTANEOUS IMPROVEMENT OF WELDER HEALTH AND WELD QUALITY OF GAS METALS ARC WELDED ALUMINUM AA5083-H112

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This study investigated the weld joint mechanical properties and welding fume exposure associated with Gas Metal Arc Welding of aluminum AA5083-H112 in 27 different welding room environment conditions. These conditions consist of variation in temperature, as well as intake and exhaust wind velocities. The temperature varies as 19 °C, 27 °C and 35 °C. Both the intake and exhaust velocity vary as 0 m/s, 3.1 m/s and 5.5 m/s. The experimental findings underscore the pronounced influence of these factors on both weld quality and welder exposure to fumes. Notably, intake wind velocity emerges as the most critical factor, contributing significantly to 47.68 % in weld joint tensile strength. The temperature emerges as the least critical factor with 12.02 % of contribution. However, temperature became the most critical factor on weld joint impact energy with 54.89 % of contribution while exhaust wind velocity became the least with 3.89 %. Air quality monitoring highlights the importance of optimal intake and exhaust fan configuration to effectively reduce fume exposure. All examined welding room environment condition are deemed safe for the welder, as they do not exceed the Treshold Limit Value (TLV), except the condition where the welding room lacks of air circulation in intake and exhaust wind velocity of 0 m/s. The identified optimal welding room condition exerts a temperature of 27 °C, intake and exhaust wind velocity of 0 m/s and 3.1 m/s respectively. This condition not only achieves established weld quality standards but also ensures compliance with fume exposure regulation. This research provides valuable insights for optimizing welding room environment to simultaneously maintain weld quality and safeguard the well-being of welders

Keywords: gas metal arc welding, AA5083, welding environment, fume exposure, tensile strength, impact energy

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1. Introduction

Aluminum alloys are highly preferred in vehicle construction due to their lightweight nature and excellent mechanical properties, which ultimately enhance fuel efficiency [1]. With the increasing demand for lightweight materials, aluminum alloy AA5083 is now commonly used in high-speed train applications [2]. However, the conventional Gas Metal Arc Welding (GMAW) technique, frequently used for joining aluminum, faces significant challenges related to both physical and mechanical aspects of the weld joint. Heat-induced changes during the fusion welding process can seriously degrade mechanical properties by altering the deposit and dendritic structures [3]. Cracking and porosity pose major concerns in welding aluminum alloys due to their high thermal expansion coefficient, significant volume change upon solidification, and wide solidification temperature range [4].

Ensuring high-quality weld joints involves meticulous attention to the performance of shielding gases during welding operations, as they play a crucial role in protecting the arc from atmospheric contaminants [1]. Among the various challenges encountered, wind-induced disturbances stand out as a primary factor that can compromise the effectiveness of shielding gas, consequently increasing the risk of welding defects [5]. Porosity represents a significant concern within the realm of aluminum alloy welding, with profound implications for the mechanical integrity of weld joints. This phenomenon arises due to the elevated solubility of hydrogen in the liquid phase of aluminum [1, 6]. As the temperature of the weld pool decreases, the solubility of hydrogen diminishes, leading to the entrapment of hydrogen bubbles within the weld metal [7]. These trapped bubbles subsequently manifest as porosity, adversely affecting the structural integrity and performance of the weld joint such as weldability and strength [8], and the toughness and crack growth parameters [9].

The welding process, characterized by extremely high temperatures, ultraviolet radiation, and metal reactions to the atmosphere, generates fumes that pose health risks to welders. Epidemiological and animal studies highlight adverse health effects such as airway irritation, bronchitis, and alterations in lung function attributable to welding fumes [10]. The concentration of inhaled fumes is contingent on the rate of fume generation and airflow to the respiratory zone. Appropriate control measures, including ventilation systems and respirators, are essential for mitigating welding fume exposure. An effective air circulation system is imperative to reduce exposure, ensuring a continuous supply of clean air to the welder's breathing area. Overexposure becomes a concern if local exhaust ventilation systems are inadequately utilized [11, 12].

Therefore, studies that are devoted on welding environmental parameters, aiming to assess their impact on both weld quality and the well-being of welders, hold significant scientific relevance. Understanding how factors like temperature, air velocity, and ventilation systems affect weld quality and worker safety contributes to informed decision-making in welding operations. By conducting research in this area, industries can implement effective measures to optimize both the quality of welds and the health and safety of personnel involved in welding processes. This emphasis on scientific investigation underscores the importance of continual improvement and advancement in welding practices to meet evolving standards and mitigate potential hazards. Therefore, studies that are devoted on welding environmental parameters on both weld quality and safeguard the well-being of welder are scientific relevance.

2. Literature review and problem statement

Previous studies on welding have typically concentrated solely on either assessing welding environmental parameters or examining fume exposure to welders. Some researchers have investigated how environmental factors impact weld quality, while others have focused on the effects of room air circulation systems on welder health.

Environmental parameters scrutinized in these studies including temperature, humidity, and air flow velocity. Previous research explored the influence of environmental temperature on the physical and mechanical properties of AA-5083 welding, finding that weld strength and hardness are higher at temperatures above 0 °C than below it [2]. The paper [2] focused on high gap of temperature condition from –20 °C to 40 °C. The effect of small gap of environment temperature has not become a focus yet. The varied environment temperature in this study intend to provide comfortable working environment to the welder. Hence, the investigation of the effect of small gap of environment temperature is required.

The welding process, characterized by extremely high temperatures, ultraviolet radiation, and metal reactions to the atmosphere, generates fumes that pose health risks to welders. Epidemiological and animal studies highlight adverse health effects such as airway irritation, bronchitis, and alterations in lung function attributable to welding fumes [10]. The concentration of inhaled fumes is contingent on the rate of fume generation and airflow to the respiratory zone. Appropriate control measures, including ventilation systems and respirators, are essential for mitigating welding fume exposure [11]. An effective air circulation system is imperative to reduce exposure, ensuring a continuous supply of clean air to the welder's breathing area. Overexposure becomes a concern if local exhaust ventilation systems are inadequately utilized [12]. A research focused on the impact of air flow velocity on shielding gas performance on MAG welding indicated suboptimal shielding gas function at an air flow velocity of 10 m/s, necessitating increased nozzle numbers to maintain shielding gas flow in windy environments [13]. This study only focused on the variation of wind velocity without increased nozzle numbers to assess the effect of environment condition solely.

The paper [8] investigate the performance of different shielding gas composition against mechanical properties of weld joint. This study retrieves information of the importance of shielding gas performance to weld quality from paper [8]. Suboptimal shielding gas protection could induce porosity and other defects. Prediction of porosity generation against hydrogen concentration conducted in paper [9]. The information of the relationship between hydrogen contamination and porosity from paper [9] utilized to strengthen the evidence of porosity formation in weld joint. The enrichment of hydrogen leads to the postulation of a wavelike distribution of pores after solidification. However, under most solidification conditions, this wavelike distribution of pores is likely blurred by pore migration in the mushy zone.

Another study examined the effects of air flow direction and velocity on steel weld quality, revealing that the best welds were achieved at an air flow velocity of 0.5 m/s [5]. The flow direction effect was not discussed in this paper due to welding room limitation of design.

The paper [5, 13] have defined the negative effects of air flow velocity on GMAW. However, the welding room requiring an air ventilation system which generate air flow to maintain the good air quality. An effective ventilation system can reduce fume concentration in the welding room so that the exposure to the welder can be minimized [14]. The modified ventilation system on the paper [14] was not applied in this study. This paper utilizing intake and exhaust fan as its ventilation system.

The study conducted in paper [11] pronounced the necessity of respiratory protection along with good ventilation system. The objective of this study is to assess the fume concentration towards different room ventilation so that the respiratory protection was not required in this paper. The paper [12] assess multiple occupational health risk of metal fumes in welding process. The fume samples in paper [12] were collected towards 15 welders during five consecutive weeks. The fume samples than analyzed and assessed based on its health risk. This paper only observes the welding room fume concentration within small scale of welding room without risk assessment due to different main focus from paper [12].

The study to explore the comprehensive influence of various environmental parameters in Gas Metal Arc Welding (GMAW) on both weld joint quality and the health of the welding room has not been found in recent studies. All this allows to assert that it is expedient to conduct a further research to investigate the impact of these environmental factors on fume exposure, facilitating a deeper understanding of how the welding environment influences both weld quality and the health risks posed to welders.

3. The aim and objectives of the study

The aim of this study is to develop welding room with controlled environment condition to maintain air and weld quality of GMAW AA5083-H112. The environment conditions are engineered by varying temperature of 19 °C, 27 °C, 35 °C, intake and exhaust fan of 0 m/s, 3.1 m/s, 5.5 m/s respectively.

To achieve this aim, the following objectives are accomplished:

– to analyze mechanical properties**:** examine the influence of individual factors of the welding room environment on the mechanical properties, specifically the ultimate tensile strength and impact energy, of AA-5083 aluminum weld joints;

– to assess air quality: investigate the effects of the welding room environment on the air quality within the welder's breathing area, considering factors that may contribute to fume exposure;

– to choose the best condition: choose the best environmental conditions for the welding room based on this research variables. This will allow to design welding room a welding room that promotes the simultaneous attainment of high-quality welds and excellent air quality, thereby safeguarding the well-being of the welder.

4. Materials and methods

The object of the study is the welding process.

Drawing insights from existing literature, several hypotheses are formulated for this study. It is hypothesized that airflow is essential for reducing fume exposure and ensuring a fresh air supply to the welder's breathing area. However, excessive airflow may disrupt shielding gas function, leading to contamination of liquid aluminum with hydrogen from the external environment. The presence of trapped hydrogen in molten aluminum is anticipated to increase porosity generation.

The experimental setup involved utilizing a 6 mm in thickness of AA5083-H112 base material, following AWS D1.2 standards for the welding coupon. GMAW was employed, using a 1 mm diameter ER5356 filler wire, to create welded joint samples. A complete joint penetration (CJP) single v-groove butt joint was executed in the 1G position using a forehand welding technique with a MIG welder. High-purity argon served as the shielding gas. The more detailed welding parameter conditions are shown in Table 1.

The welding environment was meticulously controlled, considering temperature, intake and exhaust wind velocity. A total of 27 different conditions were tested, as detailed in Table 2, and the welding workplace design is illustrated in Fig. 1.

Table 1

Welding parameter conditions

Base metal	AA 5083-H112
Base metal dimension (mm)	60×150×400
Filler rod	ER5356 (1 mm)
Shielding gas	High purity argon
Groove	60°; V-shape
Number of pass	1
Root gap (mm)	1
Welding position	Flat
Current (A)	160
Voltage (V)	22
Pulse	No pulse
Welding speed (mm/min)	190

Temperature measurements were taken with a thermometer, while intake and exhaust air velocities were measured with an anemometer at a distance of 5 cm from the fan. Subsequent to welding, mechanical and physical tests were conducted on the sample pieces, as depicted in Fig. 2. To assess fume concentration, measurements were taken in the welder's breathing area for each condition. A Krisbow Air Quality Meter 10207854 was employed for a 5-minute duration starting from the commencement of welding. The measuring instrument was positioned 5 cm from the welding mask, providing insights into the potential fume exposure under varying welding conditions.

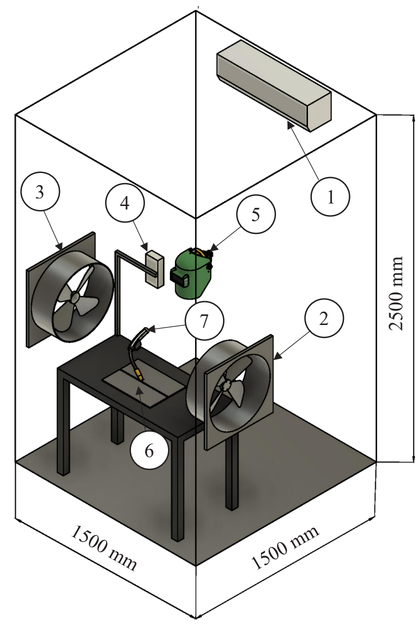


Fig. 1. Welding workplace design:
1 – air conditioner; 2 – intake fan; 3 – exhaust fan;
4 – air quality meter; 5 – welding mask; 6 – workpiece;
7 – welding gun

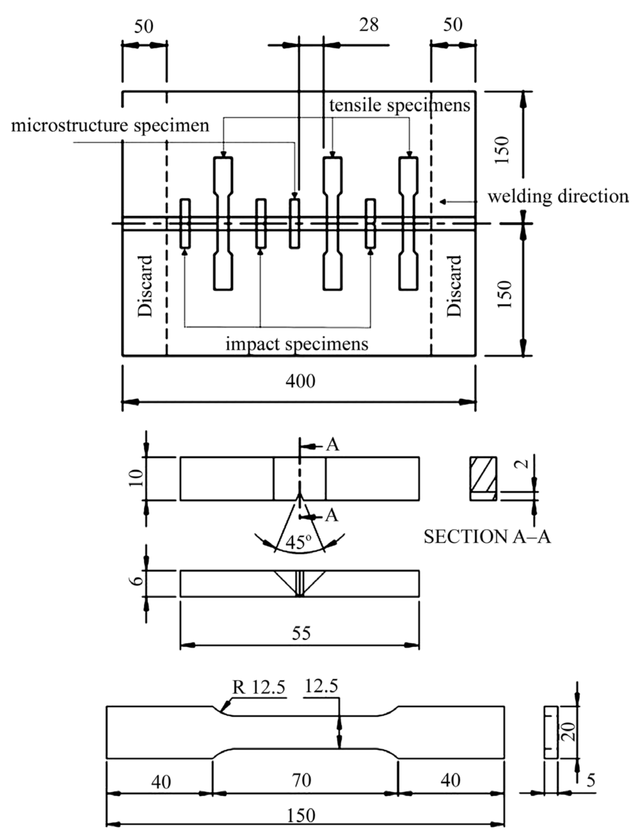


Fig. 2. Mechanical analysis test pieces

ASTM E8M-06 referred as tensile test specimen standard and ASTM E-23 referred as Charpy impact test specimen standard.

5. Result of the weldment mechanical test and welding room fume concentration observation

5. 1. The effect of welding room environment on mechanical properties of weld joint

Table 2 visually presents the impact of temperature, intake, and exhaust wind velocity within the welding room on both Charpy impact strength and ultimate tensile strength (UTS), where the first two digits represent the temperature in °C, the third and fourth digit represent the intake and exhaust wind velocity in m/s respectively.

A more detailed examination of this data can offer valuable insights to find out the relation between welding workplace conditions and the mechanical properties of the weld metal.

To explore the effect of temperature on the mechanical properties of the weldment, mechanical tests data were compared between specimen 19OO, 27OO and 35OO. Those specimens were welded under three temperature conditions, maintaining intake and exhaust air velocities at 0 m/s, as depicted in Fig. 3.

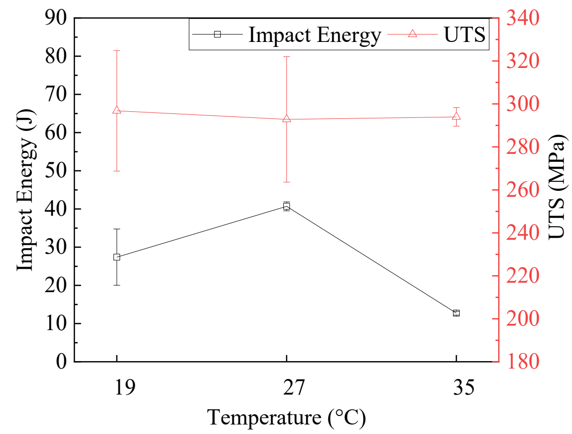


Fig. 3. Temperature – mechanical properties

Notably, the highest UTS, reaching 296.81 MPa, was achieved by specimen19OO which were welded at 19 °C. The UTS of specimens which were welded at 27 °C and 35 °C only exhibited marginal decreases of 1.37 % and 0.95 %, respectively, compared to that of at 19 °C. Given the small range of UTS (only 4 MPa) and the minor percentage changes, the welding room temperature of 16 °C does not appear to significantly affect the UTS. In contrast, the highest impact energy of 40.69 J was recorded in specimen 27OO which were welded at 27 °C. Specimens which were welded at 19 °C and 35 °C, the impact energy decreased by 32.69 % and 70.39 %, respectively, compared to that of at 27 °C. These observations highlight the considerable sensitivity of impact energy to welding room temperature fluctuations, indicating a more pronounced effect compared to UTS under varying welding room temperature conditions.

The impact surface fractures of specimen 19OO, 27OO and 35OO depicted in Fig. 4. were observed to examine the reason on the fluctuation of its impact energy. The impact fracture observed by measuring the lateral expansion to examine the fracture modes of each specimen.

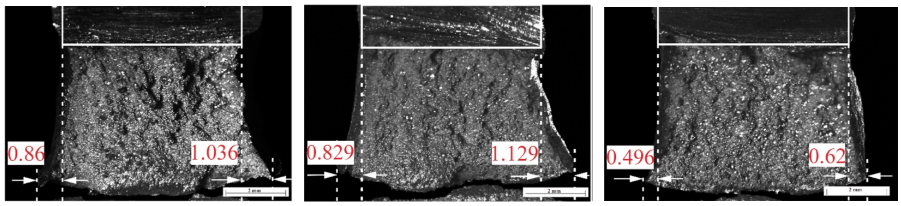
The effect of intake wind velocity in welding room on impact energy and UTS of weld joint was obtained through observing mechanical test results at three welding room temperatures with exhaust wind velocity of 0 m/s and intake wind velocity of 0 m/s; 3.1 m/s; 5.5 m/s as shown in Fig. 5.

For all welding room temperature, the highest UTS was achieved by specimens which were welded at intake wind velocity of 0 m/s.

Table 2

Mechanical testing data of joints welded in various environment condition

Condition	*T*, °C	Intake, m/s	Exhaust, m/s	Impact energy, J			UTS, MPa		
19OO	19	0	0	19.25	33.58	29.35	290.46	272.47	327.5
19OL	19	0	3.1	18.6	17.3	17.95	282.66	268.58	294.67
19OH	19	0	5.5	12.05	14.03	19.9	282.79	278.36	273.99
19LO	19	3.1	0	12.05	15.34	17.3	284.41	287.45	298.78
19LL	19	3.1	3.1	18.6	16	17.3	300.16	295.38	286.01
19LH	19	3.1	5.5	10.72	14.69	19.9	272.67	274.56	229.39
19HO	19	5.5	0	9.05	11.36	10.47	262.34	223.47	277.33
19HL	19	5.5	3.1	12.71	8.06	9.39	259.62	265.28	240.95
19HH	19	5.5	5.5	12.05	8.72	8.06	196.23	268.72	234.96
27OO	27	0	0	41.63	39.39	41.07	259.56	314.21	304.64
27OL	27	0	3.1	36.52	26.25	31.18	280.05	267.21	290.3
27OH	27	0	5.5	28.73	29.96	19.9	281.69	256.63	294.94
27LO	27	3.1	0	34.17	31.18	37.1	276.41	265.76	294.56
27LL	27	3.1	3.1	34.17	32.38	31.18	244.62	251.35	274.04
27LH	27	3.1	5.5	28.73	32.38	32.38	243.2	224.42	226.29
27HO	27	5.5	0	25	19.9	19.9	289.34	266.32	195.57
27HL	27	5.5	3.1	10.72	13.37	12.71	224.14	180.89	191.1
27HH	27	5.5	5.5	8.06	13.37	14.69	208.33	237.3	224.45
35OO	35	0	0	12.15	12.95	13.03	291.03	298.93	291.97
35OL	35	0	3.1	10.72	8.72	13.37	274.03	283.06	275.97
35OH	35	0	5.5	9.39	12.05	9.39	269.82	264.76	241.94
35LO	35	3.1	0	2.69	12.71	12.71	255.4	268.36	266.2
35LL	35	3.1	3.1	12.05	14.69	14.69	287.89	283.8	286.9
35LH	35	3.1	5.5	16	6.72	5.38	274.74	150.78	180.99
35HO	35	5.5	0	9.65	8.72	9.32	228.61	271.13	234.78
35HL	35	5.5	3.1	9.39	8.06	12.05	151.64	160.11	155.69
35HH	35	5.5	5.5	8.06	13.37	10.72	189.21	209.43	165.98



a *b* *c*

Fig. 4. Surface fracture of impact test specimen: *a* — 19OO; *b* — 27OO; *c* — 35OO

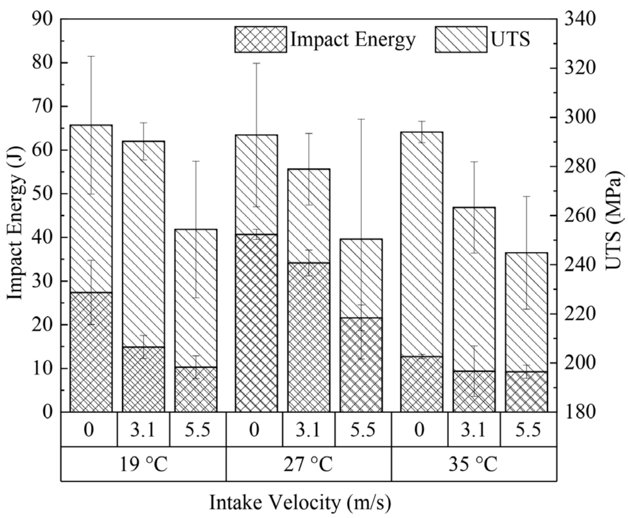


Fig. 5. Intake wind velocity — mechanical properties

The trend of UTS at three welding room temperature indicating a drop of UTS as the intake wind velocity increases. The largest drop of UTS by 16.71 %, occurred on weld joints which were welded at room temperature of 35 °C with an increase in intake wind velocity from 0 m/s to 5.5 m/s. The highest impact energy is obtained by specimens which were welded at intake wind velocity of 0 m/s at all welding room temperatures. Impact energy then decreases as the intake wind velocity increases to 3.1 m/s and 5.5 m/s. Specimens which were welded in the room with intake wind velocity of 5.5 m/s has the lowest impact energy and UTS at all temperature conditions. The cross-sectional macrograph of the weldment, as illustrated in Fig. 6 was taken to support the mechanical test data.

Observation of the cross section of the weld results shows an increase in porosity at environmental conditions of 19OO to 19LO. Porosity of 19OO and 19LO conditions was measured quantitatively with ImageJ. The number and total area of porosity in each condition is shown in Table 3.

The amount of porosity increases with increasing intake velocity in environmental conditions from 0 m/s to 3.1 m/s. Increased porosity can be caused by two factors, disruption of the function of the shielding gas and fast cooling rates.

Table 3

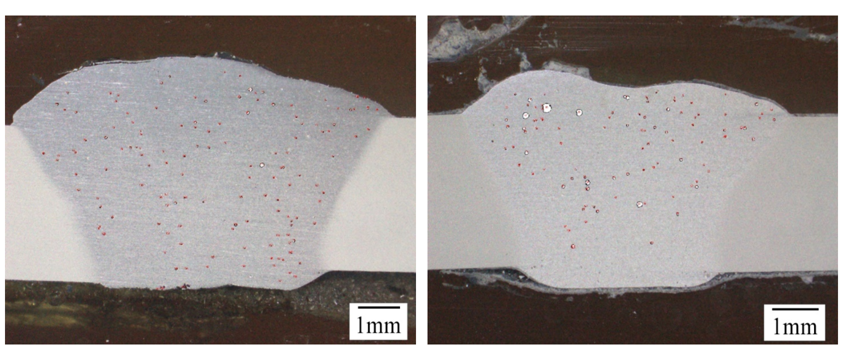
Number and total area of porosity

Condition	Porosity	Total A (mm^2)
19OO	165	0.248
19LO	109	0.572

Fig. 7 shows the incomplete penetration defect of the weld specimen in environmental conditions with a variation of intake velocity of 5.5 m/s, namely 19HO, 27HO and 35HO. Welding in environmental conditions with an intake speed of 5.5 m/s experiences welding arc instability and high material heat output due to forced cooling by too high air flow. Fig. 8 illustrates the shielding gas disruption scheme within three air flow velocity condition. The air speed condition of 5.5 m/s is notably significant in the context of Gas Metal Arc Welding (GMAW). As per the guidelines outlined in AWS D1.2, the permissible wind speed for gas welding should ideally not surpass 8 kilometres per hour or approximately 2.2 meters per second. Thus, an air speed of 5.5 m/s holds considerable influence within this framework.

In low air flow velocity of 3.1 m/s, air is sucked in between whirlpool and reaches the arc resulting in a shielding failure. With an excessive air flow velocity of 5.5 and an inadequate gas flow, no whirlpool is formed, the wire tip leaves the shielded area completely and is exposed.

The impact and tensile strength of weld joints in a welding room were assessed based on exhaust wind velocity, observing mechanical test results across three temperature conditions (27 °C, 19 °C, and 35 °C). The intake wind velocity remained constant at 0 m/s, while exhaust wind velocities varied at 0 m/s, 3.1 m/s, and 5.5 m/s, as illustrated in Fig. 9.



a *b*

Fig. 6. Cross-sectional of weld metal: *a* — 19OO; *b* — 19LO

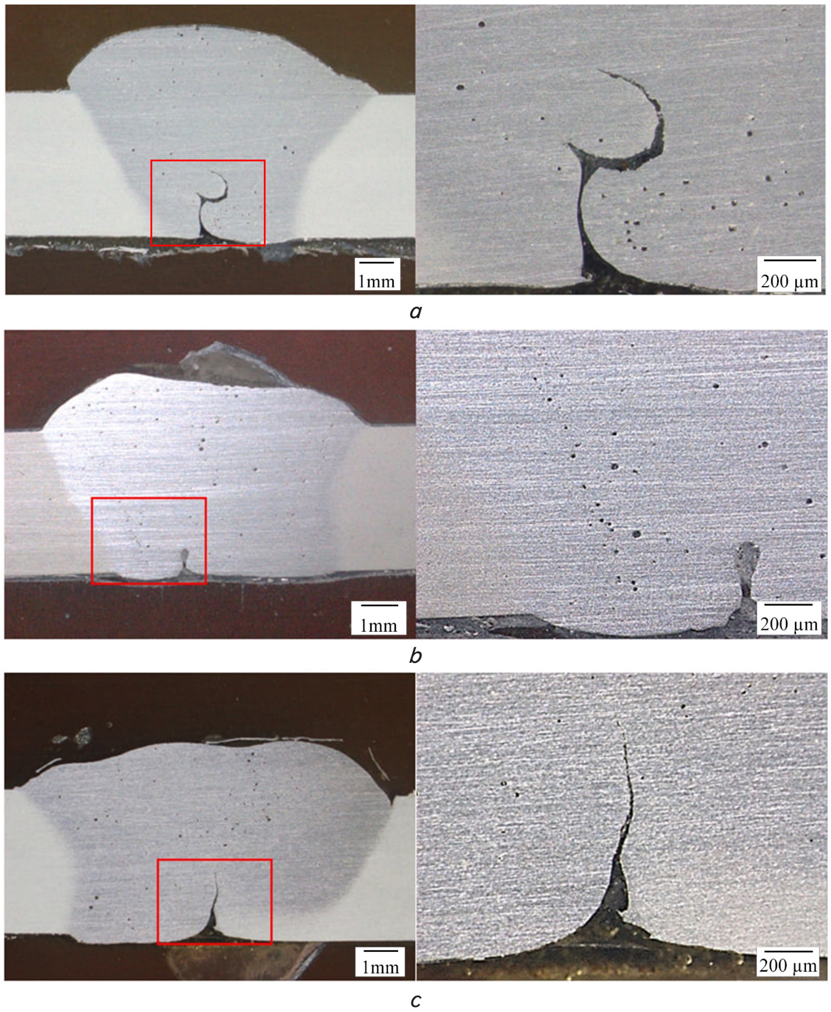


Fig. 7. Cross-sectional of weld metal: *a* – 19HO; *b* – 27HO; *c* – 35HO

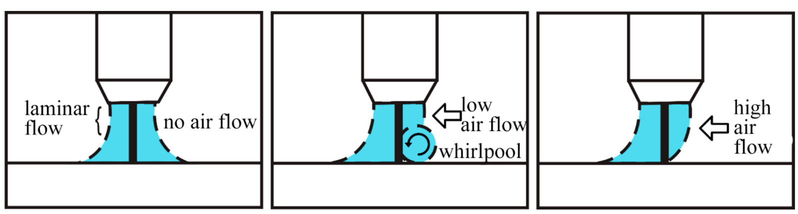


Fig. 8. Shielding gas disruption scheme

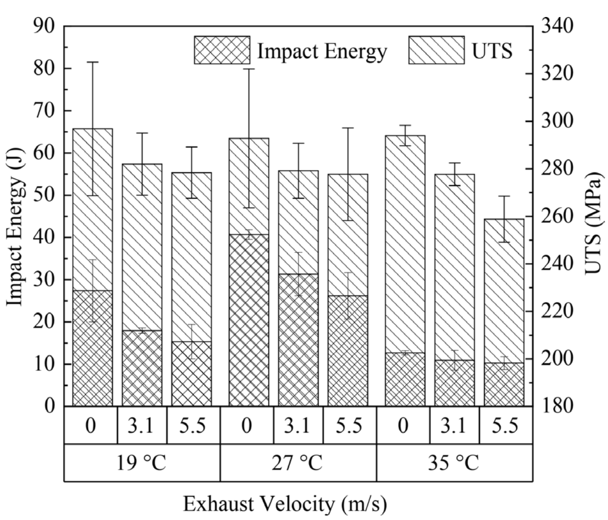


Fig. 9. Exhaust wind velocity – mechanical properties

Trends in tensile strength decline were consistent across all temperature conditions. The most significant decrease, 6.79 %, was observed in specimens welded at 35 °C with an exhaust wind velocity increase from 3.1 m/s to 5.5 m/s. Notably, the impact of exhaust wind velocity variations on tensile strength was less pronounced compared to intake velocity variations. Specimens welded at an exhaust wind velocity of 5.5 m/s exhibited the lowest impact and tensile strength at all temperature conditions. Specifically, at 35 °C, these specimens recorded the lowest impact absorbed energy of 26.19 J and tensile strength of 258.83 MPa. The declining trend in impact absorbed energy was consistent across all three temperature conditions, with the order from highest to lowest being 27 °C, 19 °C, and 35 °C.

The impact and tensile strength of weldments are concurrently influenced by the temperature, intake, and exhaust wind velocity within the welding room. The mechanical test results presented in Table 1 reveal variations in both impact and tensile strength across 27 different welding room conditions, arising from the three independent variables: temperature, intake, and exhaust wind velocity. To assess the contribution of each independent variable to the dependent variables, the ANOVA statistical test was employed. The effect of each variable is quantified as the difference between the maximum and minimum average ratios. A higher percentage contribution signifies a more substantial influence on the dependent variable. Table 4 summarizes the contributions of each factor.

Notably, intake wind velocity emerges as the leading contributor to tensile strength, boasting a significance of 47.68 %. Following closely is exhaust wind velocity, contributing 15.99 %, while temperature exhibits the lowest influence at 12.02 %.

Conversely, Table 5 reveals temperature as the dominant factor influencing impact absorbed energy, with a significance of 54.89 %. Intake wind velocity follows with a contribution of 20.77 %, while exhaust wind velocity demonstrates the least impact at 3.89 %.

These findings provide a comprehensive understanding of the varying influences of temperature, intake, and exhaust wind velocity on the mechanical properties of weld joints.

Table 4

Analysis of variance of weld joint tensile strength

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Temperature (°C)	2	4134	2067.2	4.95	0.018	12.02 %
Intake wind velocity (m/s)	2	16397	8198.7	19.62	0	47.68 %
Exhaust wind velocity (m/s)	2	5500	2750.2	6.58	0.006	15.99 %
Error	20	8356	417.8	–	–	24.30 %
Total	26	34388	–	–	–	100 %

Table 5

Analysis of variance of weld joint impact energy

Factor	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution
Temperature (°C)	2	1261.59	630.79	26.83	0	54.89 %
Intake wind velocity (m/s)	2	477.31	238.65	10.15	0.001	20.77 %
Exhaust wind velocity (m/s)	2	89.37	44.68	1.9	0.176	3.89 %
Error	20	470.25	23.51	–	–	20.46 %
Total	26	2298.51	–	–	–	100 %

5. 2. Investigation the effects of temperature, intake and exhaust wind velocity on air quality of welding room

Fig. 10 provides a visual representation of the fume concentration history throughout the welding process under diverse welding room conditions.

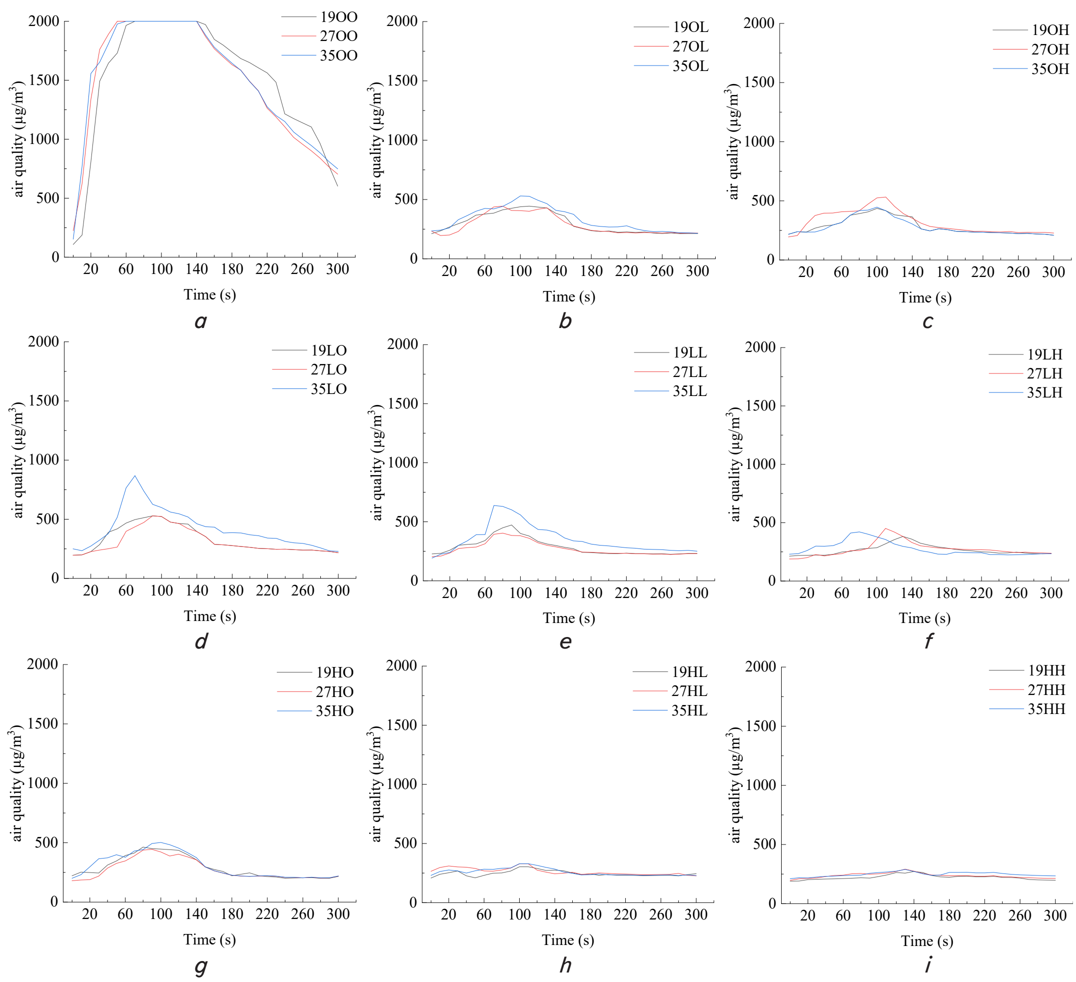


Fig. 10. The fume concentration history: *a* – 19OO, 27OO, 35OO; *b* – 19OL, 27OL, 35OL; *c* – 19OH, 27OH, 35OH; *d* – 19LO, 27LO, 35LO; *e* – 19LL, 27LL, 35LL; *f* – 19LH, 27LH, 35LH; *g* – 19HO, 27HO, 35HO; *h* – 19HL, 27HL, 35HL; *i* – 19HH, 27HH, 35HH

Fume concentration acts as a crucial indicator for assessing the air quality within the welding environment, and prolonged exposure to elevated concentrations poses potential health risks for welders, increasing the likelihood of inhaling harmful fumes. The assessment of fume concentration history takes into account the temperature, intake, and exhaust wind velocity of the welding room.

Notably, Fig. 10, *a–i* reveals that the temperature of the welding room does not exert a significant influence on its air quality level. However, when both intake and exhaust wind velocities are set to 0 m/s across all temperature levels, depicted by Fig. 10, *a*, the welding room experiences subpar air quality. Under these conditions, with no air circulation in and out of the welding room during welding, the concentration of nano-particles reaches the maximum measurement limit of 2000 μg/m^3 for approximately 125 seconds. It is only after a duration of 5 minutes following the completion of the welding process that optimal air quality is achieved in these specific scenarios.

5. 3. Optimal environment condition

The test series conducted in this study highlights the significant impact of temperature, intake, and exhaust wind velocity on both weld joint quality and welding room air quality. To obtain the best environment condition, the result of that condition must meet both weld quality standard of AWS D1.2 and air quality standard exposure of American Conference of Governmental Industrial Hygienists (ACGIH) and Occupational Safety and Health Administration (OSHA). According to AWS D1.2 the mechanical test of weld joint must pass through the minimum mechanical properties of base metal. In AA5083-H112 base metal, the minimum tensile strength is 275 Mpa and the minimum impact energy is 24 J. The air quality declared as safe condition to the welder as long as they do not surpass the OSHA Permissible Exposure Limit (PEL) of 5 mg/m^3 or ACGIH Threshold Limit Value (TLV) of 1 mg/m^3. ACGIH sets a TLV recommendation at 1 mg/m^3 to help protect workers from the health risks associated with aluminum welding fumes.

In a single graph, both mechanical test data and air quality from 27 different environmental conditions are presented in Fig 11.

Following this, the study establishes the lowest strength limit allowed by AWS D1.2 standards and the highest fume concentration limit allowed by OSHA PEL and ACGIH TLV.

Specimens with strengths surpassing 275 MPa are identified as preferred candidates, then screened based on fume concentration, as depicted in Fig. 11. From the analysis in Fig. 11, specimens meeting the AWS D1.2 standard include 19OO, 27OO, 27OL, 27OH, 27LO. These specimens undergo a secondary evaluation based on fume concentration of less than 5 mg/m^3 of OSHA PEL and 1 mg/m^3 of ACGIH TLV. The resulting in the identification of the conditions 27OL, 27OH, 27LO passed the weld and air quality standard.The condition 27OL selected as the optimal condition as it produce the best weld and air quality within three remaining condition.

6. Discussion of the effect of welding room environment to the weld quality and fume exposure

The thermal conditions during welding significantly influence crucial aspects such as microstructure, weld defects, stress distribution, and phase transformations in both the weld metal and Heat Affected Zone (HAZ) [2]. Among these factors, the temperature of the welding room plays a key role in determining heat input and cooling rates during welding [13]. Lower temperatures in the welding environment result in reduced heat input and faster cooling rates. An increased cooling rate leads to the formation of fine grains in the weld metal, enhancing strength and hardness but compromising ductility. As depicted in Fig. 3, specimens welded at a temperature of 19°C demonstrate the highest strength, attributed to their fine microstructure grains. However, these specimens exhibit low toughness due to their brittle weld zone. In contrast, specimens welded in an environment with a temperature of 37 °C show lower strength. Fig. 4 visually represents the impact surface fractures of specimens welded at room temperatures of 19 °C, 27 °C, and 35 °C, each exposed to intake and exhaust wind velocities set at 0 m/s. These specimens are labeled as 1900, 2700, and 3500, denoting the welding conditions; for example, «1900» indicates a specimen welded in a room at 19 °C, with intake and exhaust wind velocities both at 0 m/s. Upon examining the fracture surfaces of impact tests depicted in Fig. 4, the phenomenon of lateral expansion becomes evident. The lateral expansion measurements for specimens 1900, 2700, and 3500 are 1.896 mm, 1.958 mm, and 1.116 mm, respectively. This lateral expansion serves as an indicator of the material's tendency toward ductile or brittle fracture behavior. Importantly, a greater lateral expansion correlates with a higher energy requirement for material fracture, indicating increased impact strength [15]. Conversely, reduced lateral expansion implies a decrease in material ductility. Referring to Fig. 4, it is clear that specimen 3500 exhibits the lowest impact absorbed energy, aligning with its corresponding lateral expansion value. Welding specimens

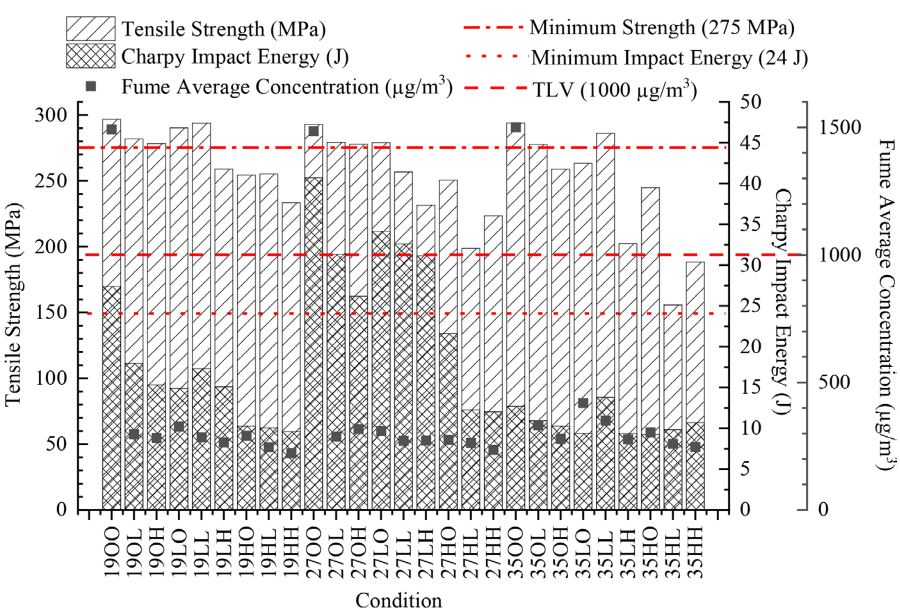


Fig. 11. Chart for selecting the best condition of welding room

within a room at 35 °C slows the cooling rate, promoting the enlargement of the grain structure in the weld metal's microstructure. Consequently, this results in a reduction in both tensile strength and impact absorbed energy.

Fig. 5 clearly indicates that an increase in intake wind velocity within welding room corresponds to a decrease in both impacts absorbed energy and tensile strength within the weld joint. These trends are further supported by the cross-sectional macrograph of the weldment, as illustrated in Fig. 6. The definition of the specimen's labels on this figure refers to Table 2. Upon closer inspection of the cross-sectional macrograph of specimens welded in a room at 19 °C, porosity is observed in the weld metal. The extent of weld metal porosity increases with the increase of intake wind velocity from 0 m/s to 3.1 m/s. The increase of porosity is corresponding to the disruption of shielding gas and the acceleration of cooling rates. The failure of shielding gas to effectively shield the welding arc leads to hydrogen contamination within the molten aluminum. Given the high solubility of hydrogen in the liquid phase of aluminum, porosity develops in the insufficiently protected molten aluminum. Moreover, the increase in intake wind velocity in the welding room contributes to a higher cooling rate, resulting in the entrapment of more air bubbles in the weld metal. The intake wind velocity of 5.5 m/s assessed to be excessive since it poses more challenges such as welding arc instability and significant heat loss [14]. Increased heat loss during welding can trigger forced cooling, impeding the attainment of optimal weld penetration and resulting in defects, as illustrated in Fig. 7. Moreover, high wind velocity within the welding environment can disrupt the effectiveness of shielding gas, which is crucial for protecting the molten metal. An open welding arc further complicates matters by compromising arc stability, thereby hindering the achievement of adequate penetration. This disruption to the shielding gas is depicted in Fig. 8, where the welding arc is exposed to the surrounding atmosphere due to high airflow velocity. The inadequate penetration caused by wind interference around the welding arc subsequently leads to a reduction in the mechanical strength of the weld, as depicted in Fig. 9.

Fig. 10 illustrates the substantial improvement in air circulation achieved through the installation of intake and exhaust fans in the welding room, effectively mitigating fume exposure for welders. The exhaust fan takes on a pivotal role in eliminating fumes produced during welding, while the intake fan ensures a continuous supply of clean air for the welder [10]. Notably, when both intake and exhaust wind velocities are set at 5.5 m/s in the welding workplace, the lowest concentration of workplace fumes is attained. This underscores the efficacy of an optimized combination of intake and exhaust wind velocities in swiftly neutralizing residual airborne contaminants from welding fumes [14]. It's crucial to highlight that, all welding room conditions investigated in this study are considered safe for welders based on OSHA PEL of 5 mg/m^3. According to ACGIH, all welding room conditions passed the TLV of 1 mg/m^3 with the exception of the conditions denoted as 19OO, 27OO, and 35OO on Fig. 10, *a* [14]. These findings affirm that the implemented variations in welding room conditions maintain a healthful working environment, aligning with the recommended safety standards for welders.

The test series conducted in this study highlights the significant impact of temperature, intake, and exhaust wind velocity on both weld joint quality and welding room air quality. Specimens welded in a room with intake and exhaust wind velocities set at 0 m/s, across three room temperature levels, meet the acceptance criteria for weld quality outlined in AWS D1.2. However, this setup leads to poor welding room air quality, falling short of the TLV. Conversely, a welding room with intake and exhaust wind velocities set at 5.5 m/s for all room temperature levels results in the best welding room air quality. Nevertheless, specimens welded under these conditions do not meet the acceptance criteria for weld quality. The analysis of variance emphasizes that intake wind velocity within the welding room significantly influences both tensile strength (47.68 %) and impact absorbed energy (20.77 %) of the weld joint. To achieve optimal weld joint quality and maintain good air quality, it is crucial to minimize intake wind velocity within the welding room which have high significance on the mechanical properties. The application of exhaust wind velocity out of the welding room, while having lower significance on the mechanical properties of the weld joint, is essential for eliminating fumes from the workplace. The specimens labeled as 27OL, welded in a room with a temperature of 27 °C, intake wind velocity of 0 m/s, and exhaust wind velocity of 3.1 m/s, meet the acceptance criteria for weld quality. These specimens exhibit an impact energy of 31.32 J and a tensile strength of 279.19 MPa. The use of an exhaust wind velocity of 3.1 m/s at the 27OL condition has proven to be effective in simultaneously maintaining a good weld joint and welding room air quality. Practically, the application of exhaust wind velocity within room ventilation system is recommended.

The relationship between the independent variable and the two dependent variables – welding room temperature and wind velocity – exhibits an inverse correlation. To illustrate, when wind velocity rises, weld joint quality typically drops while welding room air quality improves. Conversely, reducing wind velocity enhances weld joint quality but at the cost of declining welding room air quality. Our primary aim is to pinpoint the ideal environmental conditions where both weld joint and welding room air quality align with established standards.

This research obtains the effect of environment condition to the weld joint quality. However, factor such as humidity which is directly related to the porosity has not been observed yet. Besides that, thermal cycle experienced by the weld piece should be measured to facilitate more evidence on phase transformation of weldment. The measurement of fume concentration should be done with higher precision of air quality meter and measured within several location to know the flow direction of fume.

7. Conclusions

1. In terms of tensile strength, the results reveal a clear hierarchy of influence, with intake wind velocity having the greatest impact at 47.68 %, followed by exhaust wind velocity at 15.99 %, and temperature at 12.02 %. Conversely, absorbed impact energy is primarily influenced by temperature (54.89 %), followed by intake wind velocity (20.77 %) and exhaust wind velocity (3.89 %). Moreover, this study highlights the crucial role of wind velocity in shaping air quality within the welding room, emphasizing that Both intake and exhaust wind velocity have more pronounced effects than room temperature.

2. All examined welding room environment condition are deemed safe for the welder's health, as they do not exceed the OSHA Permissible Exposure Limit (PEL). the welding

room environment condition which lacks of air circulation in intake and exhaust wind velocity of 0 m/s passed OSHA PEL but not passed ACGIH Threshold Limit Value (TLV).

3. To achieve compliance with AWS D1.2 acceptance criteria and uphold air quality within permissible limits, it's essential to maintain specific conditions in the welding room. These include a temperature of 27 °C, no intake wind velocity (0 m/s), and an exhaust wind velocity of 3.1 m/s. This setup not only meets welding standards but also prioritizes a safe working environment in line with OSHA PEL and ACGIH TLV guidelines. It's advisable to utilize low exhaust wind velocity within the room ventilation system for optimal performance.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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