Friction stir welding process effects on human health and mechanical properties

Mohd Atif Wahid*

Department of Mechanical and Automation Engineering,
DTC,
Greater Noida, India
Email: wahidatif89@gmail.com
*Corresponding author

Nidhi Sharma

Department of Mechanical Engineering,
GNIT,
Greater Noida, India
Email: nid.sharma83@gmail.com

Rohit Shandley

Division of MPAE,
Netaji Subhas Institute of Technology,
New Delhi, 78, India
Email: rohit_shandley@yahoo.in

Abstract: Fabricating different parts and products are very vital for manufacturing units involving complicated shaped products. Welding is the extensively used concoction methods owing to its diverse application and intrinsic features. Manufacturing organisations commonly practice fusion welding (FW) processes leading to deleterious effects on welder's health due to fumes, gases, heat and radiations evolved. Moreover, the by-products of the FW cause environmental pollution. Hence, there is urgent prerequisite for an alternate joining process which offers substantial welder safety and eco-friendliness. Lately, friction stir welding (FSW) has developed as a joining method in which the material does not melt and recast. FSW does not encompass filler materials and other consumables gifting environmental friendliness and welder's safety. Apart from being clean process, FSW also provides improved joint properties in comparison to FW as it overpowers numerous complications causing welding discontinuities and defects. The present research has been done to provide the readers with an insight into the FW and FSW process concerning welder's healthiness and mechanical properties of the joints. Additionally, the role of ergonomics has also been discussed.

Keywords: ergonomics; fusion welding; friction stir welding; FSW; health hazards; mechanical properties.

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Biographical notes: Mohd Atif Wahid is an Assistant Professor in the Department of Mechanical and Automation Engineering at Delhi Technical Campus (GGSIPU), Greater Noida, India. He received his PhD in 2018 from Jamia Millia Islamia, A Central University, New Delhi, India. His major research interest includes advanced welding, material characterisation, optimisation of design and manufacturing processes parameters, etc. He has eight years of experience including industry, teaching and research experience. He has published more than 25 articles in reputed journals.

Nidhi Sharma is an Associate Professor in the Department of Mechanical Engineering at Greater Noida Institute of Technology (GGSIPU), Greater Noida, India. She received her PhD in 2018 from Jamia Millia Islamia, New Delhi, India. Her major research interest includes welding, optimisation of design and manufacturing processes parameters, etc. She has nine years of teaching and five years of research experience. She has published more than 25 articles in reputed journals.

Rohit Shandley received his BE in Manufacturing Process and Automation Engineering and MTech in Production Engineering from the University of Delhi (Netaji Subhash Institute of Technology). Currently, he is pursuing his PhD from IIT Jodhpur. His research interests include welding metallurgy and phase transformations. He has several papers in peer reviewed journals and has presented his research in international conferences.

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1 Introduction

Major engineering sectors such as the automotive, shipbuilding, aerospace, petroleum, and civil rely heavily on welding. The sheer variety in welding from arc-based, to resistance, to solid state, to beam-based, has made it possible to join various materials and alloys in a variety of forms (Praveen and Yarlagadda, 2005; Atabaki et al., 2014; Çam and İpekoğlu, 2017). But in spite of the diversity in the welding process, the process which still dominates today is fusion welding (FW), wherein melting of the base material (BM) takes place. Arc-based welding processes are the widely employed in FW category, with SMAW and metal inert gas (MIG) being the most popular.

Due to a variety of hazards found in the workplace environment, metal fabrication can be a potentially dangerous industry if employees do not closely adhere to safety regulations. The evaluation of the aspects of health and safety of welding fabrication and repair activities is rather complex, because of the great number of disciplines involved. These may include physical aspects, i.e., radiation, heat, noise, etc. and chemical aspects, as concerning gases and particulate matters produced during welding and other hazardous chemical substances used during all phases of the fabrication process. Temperatures more than 3,000°C are common in FW. The high temperatures generated during the process give rise to toxic gases, fumes, and radiation as by-products which have deleterious consequences on the health of the welder (Antonini, 2003). With advancements in the semiconductor industry, many of the manufacturers make use of sophisticated electronics in their machines and provide features such high frequency starts, which engender electromagnetic noise. Sustained exposure to these by-products might lead to chronic lung conditions, damage of nervous system, heart diseases, dermatological, hypersensitivity effects, etc. (Antonini, 2003; American Welding Society, 1979; Stern et al., 1986).

A solid state welding process called friction stir welding (FSW) developed by The Welding Institute, UK, is revolutionising the welding world (Thomas et al., 1995). In the FSW process, joining without melting of the BM takes place, thus avoiding health hazards associated with conventional welding (Dawes and Thomas, 1996). Being an environmentally safe process, this method of joining is extremely safe for the operator from a health and safety viewpoint as hazardous, fumes, gases; vapours, radiation, and electromagnetic noise are eliminated (Akinlabi, 2012; Welder's Guide to the Hazards of Welding Gases and Fumes, https://www.work.alberta.ca/documents/WHS-PUB_ch032.pdf). In addition, FSW produces a weld quality far superior to FW, and is capable of welding solution strengthened alloys considered non-weldable by FW (Zhao et al., 2010; Rana et al., 2012; Mishra and Ma, 2005). The potential health hazards of FW and the benefits of FSW are discussed in subsequent sections.

2 Health hazards associated with FW

The numerous health hazards caused by the FW processes are discussed in this section.

2.1 Health hazards due to inhalation

Exotic gases, fumes and vapours inhalation causes notable health threats to the welders. The extent of inhalation of these by-products is measured in terms of exposure time, nature of contamination and its absorption in the respiratory tract. As the gases and fumes are less than one micrometre they enter deep into the breathing tract. Figure 1 shows particle sizes for a number of familiar pollutants (http://www.nortonsandblasting.com/weldhealth2.pdf). It is also found that concentration of particulates in breathing tract of welder is nearly four times more as compared to non-welder as shown in Figure 2 (Nastiti et al., 2012).

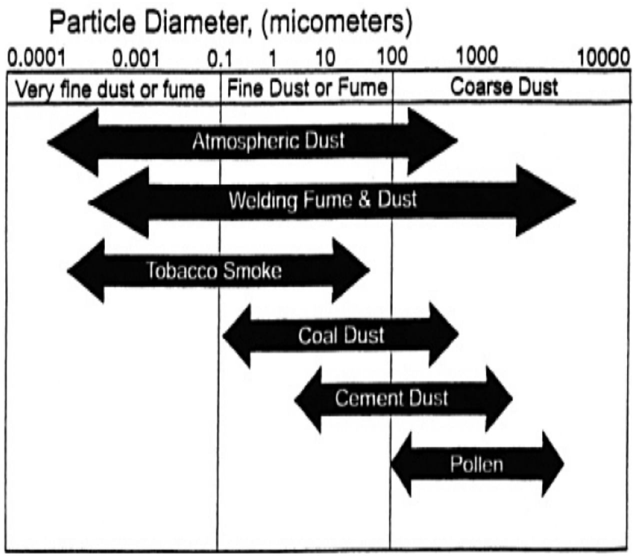
2.1.1 Effect of inhaled gases

Gases generally evolve due to arc reaction with the atmospheric gases, disintegration of electrode coating material, decomposition of degreasing agents and coatings, etc. Health hazards associated with FW gases are summarised in Table 1.

2.1.2 Effect of fumes inhalation

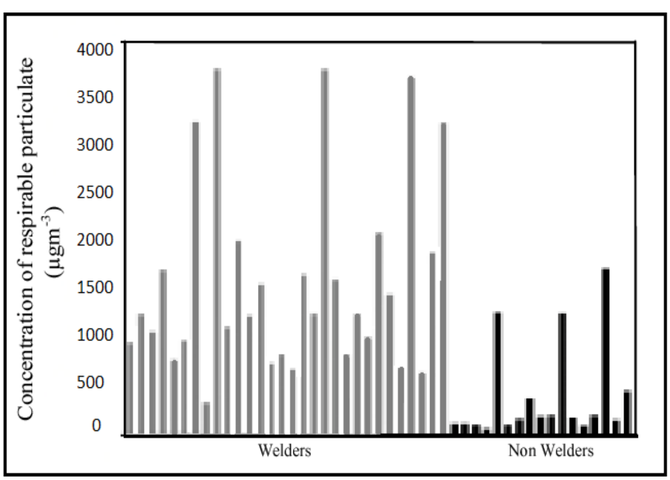
Fumes consist of metals, metal oxides and other compounds volatilised from the base metal, electrode, or flux material. Fumes of aluminium, copper, nickel, iron oxide, etc. are produced owing to the intense heat of the arc during FW. Inhalation of fumes can cause metal fume fever, bronchitis, asthma, kidney damage and emphysema, lung cancer, damage to central nervous system and reproductory organs, etc. Health threats related to FW fumes and vapours are summarised in Table 2.

Figure 1 Particle size of different pollutants



Source: http://www.nortonsandblasting.com/weldhealth2.pdf

Figure 2 Concentration of respirable particulate in breathing zone of welder and non-welder



Source: Nastiti et al. (2012)

Table 1 Health hazards associated with gases during FW

Gas	*Effects*
Carbon monoxide	Absorbed readily into the bloodstream, causing headaches, dizziness or muscular weakness. Large absorption may cause unconsciousness and prove fatal.
Hydrogen fluoride	Eyes irritation and breathing tract infection. Prolonged exposure leads to lung and liver damage. Chronic irritation.
Nitrogen oxide	Low absorption causes irritation of eyes and nose, excessive concentration's causes abnormal fluid in the lung.
Oxygen	Psychosomatic misunderstanding, weakness, suffocation and death.
Ozone	Serious consequences comprise uncharacteristic fluid in the lungs and bleeding. Low concentrations (e.g., one part per million) cause headaches and aridness of the eyes.

Source: Welder's Guide to the Hazards of Welding Gases and Fumes, https://www.work.alberta.ca/documents/WHS-PUB_ch032.pdf

Table 2 Health dangers associated with fumes and vapours during FW

Fumes/vapours	*Effects*
Aluminium	Respiratory tract infection, pneumoconiosis (Welder's Guide to the Hazards of Welding Gases and Fumes, https://www.work.alberta.ca/documents/WHS-PUB_ch032.pdf)
Beryllium	Metal fume fever and damage to the respiratory tract (Welder's Guide to the Hazards of Welding Gases and Fumes, https://www.work.alberta.ca/documents/WHS-PUB_ch032.pdf, http://www.nortonsandblasting.com/weldhealth2.pdf)
Manganese	Acute lung inflammation, Parkinson disease and tingling sensation (Flynn and Susi, 2009)
Chromium	Urinary tract infection, lung cancer. Skin and eye damage includes dermatitis, itching and rashes on forearms, carcinogenic [chromium(VI)] (Meeker et al., 2010; Kalliomäki et al., 1984)
Silicon	Silicosis, muscle and joint pain
Nickel	Potentially carcinogenic and irritating respiratory track (Kalliomäki et al., 1984)
Metal oxides	Patients experience chills, malaise, fever and joint pains, sore throat and congestion, chest tightness and fatigue. Metal fume fever (Antonini, 2003)
Fluorides	Irritation to eyes, nose and throat. Pulmonary edema and bone damage (Antonini, 2003)
Aldehydes	Irritant to eyes and respiratory system (http://www.nortonsandblasting.com/weldhealth2.pdf)

2.2 Exposure to radiation

Harmful ultraviolet (UV) and electromagnetic radiations are released during FW. Ocular malignancy and skin cancer due to UV radiation exposure is being debated (Dixon and Dixon, 2004). Along with UV, infrared (IR) radiations emitted in short and intense manner may injure the retina, while longer wavelengths may cause thermal damage to aqueous humour and cornea, as well as lenticular cataract. Some of the common harmful effects of electromagnetic radiations are as shown in Table 3.

Table 3 Effect of electromagnetic radiations

Microwave radiation	*Optical radiation*	*Ionising radiation*
Cataract	Skin cancer	Queasiness
Disorder of nervous system	Damage of retina	Cancer
Memory loss	Stress in heart	Erythema
Wooziness	Alteration in genetics	Changes in blood cell
Headache	Asthenopia	Diarrhea

2.3 Effect of noise

The exposure to welding noise may induce hearing loss among welders. In a study conducted at the Academy of Finland reported impulse noise to be more harmful as compared to continuous noise. Research conducted by Mäntysalo and Vuori (1984) also reported the loss of hearing of workers was more prominent when exposed to impulse noise.

2.4 Effect of heat

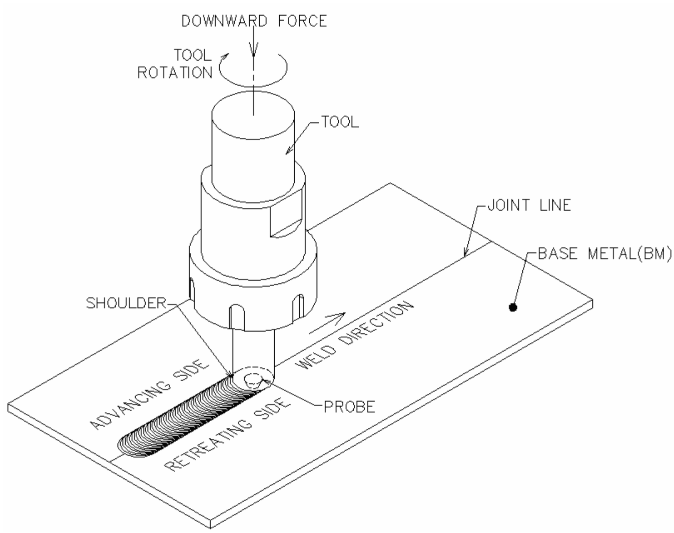
Hot metal always exists in welding and sometimes to improve weldability, material is also heated. Effects of heating are burning of skin, hyperthermia, etc. Sparks, hot molten metal, spatter and slag can also cause burns during welding.

3 Friction stir welding

FSW as a solid state process involves intense thermo-mechanical deformation. FSW utilises heat caused by friction between the tool and BM and plastic deformation caused by stirring of the tool. Principally FSW is an autogenous process in which a spinning non-consumable tool harder than the BM is inserted into the BM as the downward vertical force is provided. The side, at which the tool rotates in the same direction as the welding direction is termed as *advancing side* (AS) and the side where tool rotation opposes the welding direction, is termed as *retreating side* (RS). The localised welded region temperature increases due to the tool-BM interfacial friction causing material softening in and around the pin leading to the BM deformation. The profiled tool simultaneously navigated along the joint line initiating the movement of the BM at both sides, i.e., AS to RS. Additionally, the shouldered tool consolidates the BM at the rear of the pin offering the joint in solid condition (Wahid et al., 2016; Siddiquee and Pandey, 2014; Çam and İpekoğlu, 2017). The primary dissimilarity between FW and FSW is that no supplementary heat is supplied during the FSW as the heat is evolved due to the friction amidst the spinning tool and the BM. The schematic of the process is depicted in Figure 3.

FSW is versatile, energy efficient and environmental friendly process. The foremost facet of FSW process is the temperature at which the welding takes place which stays lower than the BM starts melting. Since the BM melting is not involved, various problems (porosity, blow holes, etc.) related to FW does not exist in FSW providing exceptional mechanical strength and elongation. FSW also does not need different consumables (electrode, shielding gases, filler materials, fluxes, etc.) which make it enormously harmless for the worker from a health and safety viewpoint as hazardous, fumes, gases, and vapours are eliminated. Moreover, this process requires vey less input energy and harmful radiations (UV, IR and visible light) that are frequently generated in arc welding, laser welding, soldering, and torch welding are not produced in FSW. Due to this, FSW is often termed as a clean and sustainable technology. Some researches performed on FSW and MIG welding of AAs have shown presence of particulate emission. It was observed that the emissions from FSW are far less as compared MIG process thus eliminating the need of filtration unit as required in MIG (Pfefferkorn et al., 2010; Cole et al., 2007).

Figure 3 The principle of FSW process



3.1 Mechanical properties of the FSW joints

Improved mechanical properties (tensile strength, hardness, etc.) of the joint produced during FSW as compared to FW are observed by various researchers (Cavaliere, 2013; Amardeep and Mangshetty, 2015; Navyashree and Sivaramakrishna, 2015). Amardeep and Mangshetty (2015) studied mechanical properties of the joint of AA7075/AA6063 produced using TIG and FSW process. Due to limitation in the precipitation dissolution and coarsening level better mechanical strength and hardness was observed in FSWed joint. Equivalent conclusions were also observed by Navyashree and Sivaramakrishna (2015) during FSW and TIG of AA 6082. Differences in mechanical properties are also obtained due to variation in microstructural features across the different zones in FSW due to severe plastic deformation and intense heat for heat-treatable and strain hardened AAs. From various studies performed on heat treatable (Chen et al., 2015; Wahid et al., 2018a) and strain hardenable (Guo et al., 2017) it is concluded that joint efficiency is good for strain-hardenable AAs. During FSW strength loss due to cold work in different zones, refinement of grains in SZ and grain coarsening in TMAZ/HAZ during welding of strain hardenable AAs takes place (Guo et al., 2017; Rao et al., 2013) while dissolution of strengthening precipitates, refinement of grains in SZ, precipitates and grains coarsening in TMAZ/HAZ takes place during FSW of heat-treatable AAs (Wahid et al., 2018a; Wahid et al., 2018b, 2019).

During FSW due to bulk material melting and low temperature involved optimum heat generation and material flow takes place leading to elimination of various solidification defects associated with the FW process. Furthermore, due to reduced thermal heat limited residual stresses are generated keeping in check the distortion and dimensional stability of the component. Finally, intense thermal and mechanical deformation encourages dynamic recovery and recrystallisation which leads to finer grains in the stir region (Siddiquee and Pandey, 2014; Çam and İpekoğlu, 2017; Wahid et al., 2019). The microstructure evolved during the FSW depends upon the combination of temperature and the strain rate achieved during the welding. Different metallurgical phenomenon, i.e., recovery, recrystallisation and grain growth during FSW depend upon the type of material, temperature (heat) involved and change in strain (deformation) with respect to time. The welded material undergoes dynamic recovery and recrystallisation both of them constitutes grain refinement. Due to these above discussed reasons good mechanical properties are observed in FSW (Wahid et al., 2018b, 2019) and this process finds widespread application in joining of different material and alloys (aluminium, magnesium, copper, etc.) used in marine, aerospace and off-shore construction (Mishra and Ma, 2005; Wahid et al., 2016; Çam and İpekoğlu, 2017). The major advantages of FSW are summarised in the Table 4.

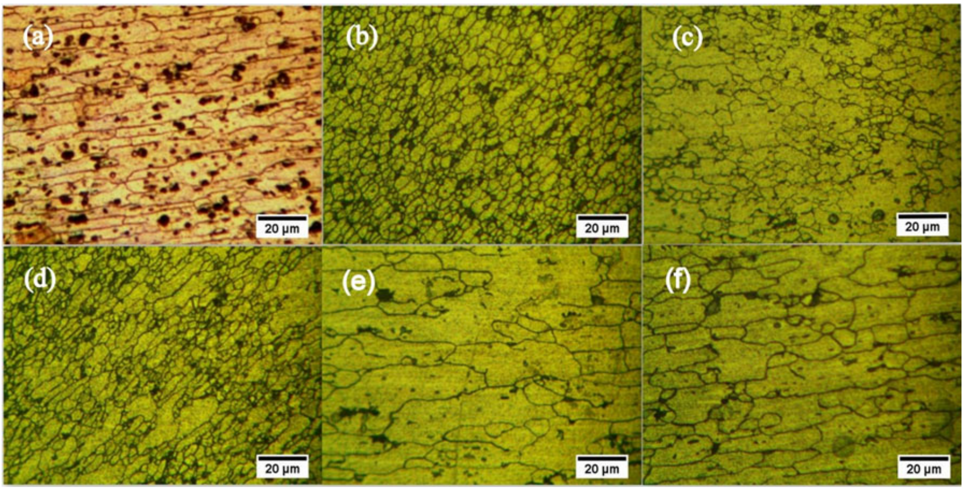
Table 4 Benefits of FSW

Metallurgical benefits		*Environmental benefits*		*Energy benefits*	
1	Absence of solidification welding defects	1	No requirement of FW consumables.	1	Reduced consumption of fuel in lightweight aircraft, ship, etc. applications.
2	Outstanding mechanical properties.	2	No release of toxic fumes		
3	No alloying element loss	3	No harmful radiations.	2	Allows considerable weight savings.
4	Refined microstructure	4	Minimal surface cleaning		
5	Low distortion and residual stresses	5	Eliminates grinding wastes.		

3.2 Ergonomics in FSW

In FW process welder need to bend and stretch a lot during the operation which tends to have high impact on their backbone and might also cause back problem in the future. Contrarily in FSW process welder does not need such kind of hard work. The operator need to just set the tools and fix the plates to be welded so there is no bending and stretching which reduces the stress from welder's backbone. Hence, the comfort of undergoing an FSW process is much more than FW processes as only machine parameters have to be set and the welding takes place easily. Several organisations conduct a strength programs for welders to keep them in proper shape and condition (Krüger et al., 2015). In strength training program, welder learns to execute the task without taking much muscles load and stress on the body which helps them to consume less energy and strength. Training provides much better work ergonomics. This could increase the muscular strength of the workers and hence would be able to perform the FSW process with less fatigue which would result in a higher productivity.

Figure 4 The microstructure of different zones for during underwater FSW of AA 6082-T6, (a) BM (b) stir zone (SZ) (c) thermo mechanically affected zone (TMAZ)-AS (d) TMAZ-RS (e) heat affected zone (HAZ)-AS (f) HAZ-RS (see online version for colours)



Source: Wahid et al. (2019)

4 Conclusions

Construction and fabrication works in the developing nation like India are performed by welding as such welder's health and safety is the first priority. Spatter fumes, radiation and particulates generated during FW cause the harmful health and environmental effects. Sustained exposure to these products tends to cause various diseases associated with heart, lungs, skin and neurology. As such bearing in mind the future technological advancements in India, FSW can be implemented by the welders due to its environment friendly behaviour and health safety benefits. Key features of FSW are its low energy input and no need of flux, filler material or shielding gases. FSW also does not emit smoke, fumes, or gases thus offering great health safety for the welders. Moreover, due to defect free joining and good mechanical properties FSW finds its extensive application in joining of different alloys used in various applications. As every process wants to achieve minimum waste and maximum environment-friendliness, FSW bestows the green technology solution for the engineering industry. FSW process is better way to increase the productivity and allowing relaxation to the welders from the stress and pressure ergonomically.

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