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Steel Weld Metal Deposit Measured Properties after Immediate Micro-Jet Cooling

Bożena Szczucka-Lasota [1], Bożena Gajdzik [2,*], Tomasz Węgrzyn [3] and Łukasz Wszołek [4]

1. Department of Technical Sciences, University of Occupational Safety Management, 40-007 Katowice, Poland; bszczucka-lasota@wszop.edu.pl
2. Department of Engineering Production, Silesian University of Technology, 40-019 Katowice, Poland
3. Transport Department, Silesian University of Technology, 40-019 Katowice, Poland; tomasz.wegrzyn@posl.pl
4. Transport Department, Vocational Training Center, 41-400 Mysłowice, Poland; lukasz.wszolek@oszk.pl

* Correspondence: bozena.gajdzik@polsl.pl; Tel.: +48-32-603-4111

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Abstract: The aim of this paper is to present a welding process connected with micro-jet cooling. This method allowed us to guide the metallographic structure, and furthermore, the properties of the weld metal deposit. The main conclusion of this paper was that after welding with micro-jet cooling, it was possible to achieve beneficial metallographic structures that are impossible to obtain in any other way. These structures corresponded to very good mechanical properties of the welds. The research results described the influence of an artificially enhanced amount of acicular ferrite in the weld metal deposit (WMD) even above 65% when using micro-jet cooling. The results of this process were very positive due to the very high impact toughness of welds at negative temperature. The main parameters of micro-jet cooling are: cooling stream diameter (about 60 μm), gas pressure (about 0.6 MPa), the use of various gases and gas mixtures (main micro-jet gases: argon, helium, nitrogen, carbon dioxide, oxygen, air).

Keywords: steel welding; micro-jet cooling; impact toughness; microstructure; WMD—Weld Metal Deposit

1. Introduction

The welding production process in particular metallurgical companies is dependent on many factors, and new techniques and materials for steel welding are still tested. Micro-jet cooling has recently been invented for both steel welding and HVOF (high velocity oxygen fuel) technology [1–4]. It is important to give weld structures good impact toughness and strength [5–8]. In the previous work described in Reference [2], the authors only analyzed argon as a micro-jet gas, and their results were very limited with regard to actual knowledge and experience. Properties of the weld metal deposit are dependent on many factors, including chemical composition, welding technology, filler materials, and state of stress. Chemical composition can first be treated as a main factor influencing the impact toughness and strength of the weld metal deposit (WMD), and very often in the deflection of long structures. For instance, some alloy elements—especially nickel (in the range of 1–3%), molybdenum (in the range of 0.2–0.6%), and oxygen (below 500 ppm)—could be treated as factors that positively influence impact toughness [2,5]. The goal of this paper was to analyze the mechanical properties of the steel weld structures after using the innovative welding process based on micro-jet cooling. The mechanical properties of steel weld structures with micro-jet cooling were much better in comparison with the standard processes. After long structure welding, this method saw a decrease in deflection.

2. Literature Review

For a long time, researchers have tried to modify metallographic structures. In low alloy steel structure, it is very important to lift the percentage of acicular ferrite (AF) in the weld as much as possible. Attempts to achieve a content of acicular ferrite above 55% in the weld metal deposit have not been successful in standard processes such as metal inert gas/metal active gas (MIG/MAG), Manual Metal Arc (MMA), submerged arc welding, and even in laser welding processes [7,8]. Acicular ferrite is a fine Widmanstätten constituent which is nucleated by an optimum intra-granular dispersion of oxide/sulfide/silicate/nitrite particles [9,10]. The role of non-metallic inclusions (mainly oxides and nitrides) during the austenite-acicular ferrite conversion was proven [5,9], where small inclusions (in the range of 0.3–0.6 μm) could be beneficial for the formation of acicular ferrite in welding conditions. Nevertheless, the presence of beneficial inclusions such as TiO, TiN, and $MnAl_2O_4$ with a lattice parameter similar to ferrite could not guarantee more than 55% of AF in the WMD [5]. This microstructure is advantageous over other microstructures due to its chaotic ordering, which increases toughness [6,9,10].

It has also been found that some oxide inclusions may modify the shape of the Charpy V impact curve as a function of temperature—especially the upper and lower toughness shelf [11]. Particularly favorable is the influence of both TiO and $MnAl_2O_4$ inclusions on the impact strength [9,11]. The amount of oxygen in the weld metal deposit corresponded directly with the size and chemical composition of the inclusions. It is believed that the main deoxidizers (Si, Mn, Al, Ti, B) should be present in the WMD in a very precise domain where manganese should not exceed 1 wt %, silicon should not exceed 0.5 wt %, titanium should not exceed 0.003 wt %, aluminum should not exceed 0.03 wt %, and boron should not exceed 0.0003 wt % in the WMD [12]. The influence of aluminum as an important deoxidizer is described in the Japanese Nippon Steel Corporation patent [13], which reports that the low impact toughness of the WMD could be explained by too high an Al content (0.12 wt %). In contrast, the American patent of Incorporated Teledyne [14] states that the amount of aluminum should be at a minimum level of 0.03 wt %. These results have been further confirmed by the results obtained by Evans [12,15,16]. The increase in impact toughness can be achieved in many ways: titanium and boron are important in the formation of oxides and nitrides; aluminum has a higher affinity for oxygen; and titanium has a higher affinity for nitrogen [17,18]. Titanium and boron are more affected by the increase in strength rather than impact toughness, which may not be beneficial [19]. The optimum titanium content of the welded electrode is dependent not only on the oxygen content of the weld, but also on the content of other elements—especially C, Al, B, and N. Masumoto [20] concluded that the optimum titanium and boron content in the weld metal was 0.01–0.05 wt % Ti and 0.001–0.003 wt % B, respectively. Titanium can also get into the welded steel. The Teledyne Incorporation patent [14] states that the optimum titanium content in the base electrode WMD should be present in the WMD at a level lower than 0.07 wt %. In the AWS E7018 electrode, the optimum titanium content was in the range of 0.002–0.07 wt %. The strength of the weld grew rapidly with an increase in titanium, but the best impact toughness of the weld metal deposit was reached with 0.03 wt % Ti. Titanium is often introduced into the WMD together with boron, though there is usually approximately 10 times more titanium than boron in the WMD [9,11]. According to the Nippon Steel Corporation GB20150337B patent, the most beneficial amount of those elements should be on the level of 0.03–0.05 wt % Ti and 0.005–0.007 wt % B, respectively. There is also a view that boron segregates to the austenite grains and hinders ferrite nucleation [9,21,22].

Thewlis [9,11] also emphasized the importance of beneficial inclusions in the formation of acicular ferrite and stated that the alloy containing Al, Ti, and B formed the non-metallic inclusion $MnAl_2O_4$ (galaxite) instead of $MnO{\cdot}SiO_2$. Galaxite has the exact same lattice parameters as ferrite. The average size of these inclusions ranges from 0.32–0.38 μm, which could be treated as optimal and corresponds to the amount of acicular ferrite in the WMD at a level of 50% (assuming that the average size of inclusions in the WMD is between 0.2–1 μm). Ahlbom [23] concluded on the basis of a literature review that the high impact toughness of low alloy weld metal deposits was dependent on the amount of oxygen. Węgrzyn [24] suggested that the division in the welding processes into oxygen and nitrogen content in metal was initiated by Ti. All-time research did not allow the acicular ferrite content to be raised in the weld metal deposit.

Recently, a micro-jet cooling application in steel welding and spray technologies has been invented as micro-jet cooling after the MAG welding process as a way of obtaining weld metal deposits with a higher amount of acicular ferrite (AF) in the weld metal deposit (WMD) that is not possible to achieve in standard metallurgical methods. Generally, the metallographic structure of WMD with elevated amounts of acicular ferrite corresponds to a much higher impact toughness. It is possible to obtain this phase in a weld due to precise and selective micro-jet cooling just after welding, where acicular ferrite can be achieved at a much higher percentage instead of grain boundary ferrite, which does not have time to grow [25]. The main parameters of micro-jet cooling can be varied: (1) cooling stream diameter (between 40–60 µm), and (2) gas pressure (between 0.4–0.7 MPa). Micro-jet gases and its mixtures were treated as a main influencing factor on the formation of acicular ferrite (argon, helium, nitrogen, air). General assumptions of an innovative welding process with micro-jet cooling are presented in this paper. This investigation has proven that the new micro-jet technology still has the potential for growth, and might be a great achievement in welding technology to steer weld metal structure and the corresponding impact toughness. Micro-jet cooling also allows for a smaller deflection—especially in the long weld structures. Micro-jet cooling can also be treated as a very good direction in surface welding due to the excellent tribological properties of the welded layers [26,27]. The use of modern techniques is an attempt to optimize the production systems connected with welding and foundries. Micro-jet cooling was also tested in foundries, and can be used as the econometric model based on the methodology proposed by Szymszal et al. [28].

3. Experimental Procedure

New micro-jet cooling technology [1–4] can be regarded as an innovative way to steer metallographic structures. This paper describes the influence of an artificially elevated amount of acicular ferrite in WMD to above 65% using micro-jet cooling. The weld metal deposit was prepared by the MAG process with micro-jet cooling through varied tested gases and mixtures. The micro-jet injector was installed just after the welding head (classic welding MAG procedure) to obtain the weld metal deposit (Figure 1).

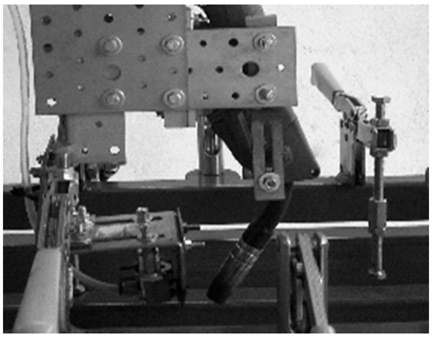

Figure 1. MIG/MAG (metal inert gas/metal active gas) welding head with micro-jet injector (experimental setup).

Only some parameters of the micro-jet cooling varied slightly:

- cooling stream diameter was not varied (always 60 µm);
- gas pressure was not varied (always 0.6 MPa);
- micro-jet gases were changed (argon, helium, and air);
- micro-jet gas mixtures were changed (90 vol % argon-10 vol % carbon dioxide, 90 vol % argon-10 vol % helium, and 90 vol % argon-10 vol % air).

The basic material of the research was S355J2G3 steel (typical C-Mn steel for welding structures). The weld metal deposits of standard MAG welding were compared with deposits obtained with and without micro-jet cooling. A typical weld metal deposit had a similar chemical composition in all tested cases (Table 1). The main data on the parameters of the MAG welding are shown in Table 1.

Table 1. Parameters of the MAG (metal active gas) welding process.

No.	Parameter	Value
1	Standard current	220 A
2	Voltage	24 V
3	Shielding welding gas	90% Ar-10% CO_2
4	Micro-jet gas pressure	0.6 MPa
5	Micro-jet gases	He, Ar, Air
6	Micro-jet gas-mixtures	90 vol % argon-10 vol % carbon dioxide 90 vol % argon-10 vol % helium 90 vol % argon-10% air
7	Micro-stream diameter	60 µm [1]

[1] Own research.

A typical weld metal deposit contained various amounts of oxygen and nitrogen after micro-jet cooling (Table 2). The chemical composition of the WMD without micro-jet cooling is presented in Table 2.

Table 2. Chemical composition of the weld metal deposit (WMD) after MAG welding.

Element	Amount
C	0.08%
Mn	0.8%
Si	0.42%
P	0.012%
S	0.013%
O	370 ppm
N	55 ppm [1]

[1] Own research.

Various micro-jet parameters had some influence on intensive cooling conditions, but did not have a greater influence on chemical WMD when Ar or He were used in that procedure. Using other micro-jet gases and gas mixtures, only variable oxygen and nitrogen content (LECO detector) were obtained in the weld metal deposit (Table 3).

Table 3. Oxygen and nitrogen in the WMD after MAG welding with micro-jet cooling.

Micro-Jet Gas	O Amount, ppm	N Amount, ppm
Ar	370	55
He	370	55
N_2	370	70
Air	450	65
90 vol % argon-10 vol % carbon dioxide	390	55
90 vol % argon-10 vol % helium	370	55
90 vol % argon-10 vol % air	390	60 [1]

[1] Own research.

The metallographic structure of WMD was further evaluated (light microscopy, etched by nital). The acicular ferrite in the WMD after MAG welding with micro-jet cooling (MeTilo) is presented in Table 4.

The AF in the WMD was analyzed using a Hitachi S.4200 (Gray) scanning microscope (magn. 1000×, Silesian University of Technology, Katowice, Poland) equipped with a video card and a camera. This allowed for the observed structure to be saved as a bmp file for loading data to the MeTilo program. The photographic documentation was done at an 800 × 600 screen resolution. An area for analysis and the phase under study was selected. Using MeTilo measuring tools (Silesian University of Technology, Katowice, Poland), the image was analyzed using mathematical morphology methods. The percentage of acicular ferrite in the WMD was achieved as a result of that test, and was also tested by X-ray analysis as an additional observation.

Table 4. Acicular ferrite in the WMD after laser welding with various micro-jet parameters.

Micro-Jet Gas or Mixture	Acicular Ferrite in WMD, %
Without micro-jet cooling	45
Ar	69
He	62
Air	53
90 vol % argon-10 vol % carbon dioxide	65
90 vol % argon-10 vol % helium	59
90 vol % argon-10 vol % air	57 [1]

[1] Own research.

By analysing Table 4, it was easy to deduce that MAG welding with micro-jet cooling could be considered as a very good option. Furthermore, it was also easy to see that MAG welding with argon (gas mixture Ar-CO_2) micro-jet cooling could be treated as the best option when compared with MAG welding without micro-jet cooling. Acicular ferrite with percentages above 45% (that corresponded to WMD without micro-jet cooling) was achievable for all tested cases (welding with various gases and mixtures) at micro-jet cooling. Acicular ferrite with percentages above 60% was only obtainable for MAG welding with micro-jet cooling by argon, helium, and one tested gas mixture (90 vol % argon-10 vol % carbon dioxide) as shown in Figure 2, where the scale of the figure does not allow for the AF to be pinpointed precisely.

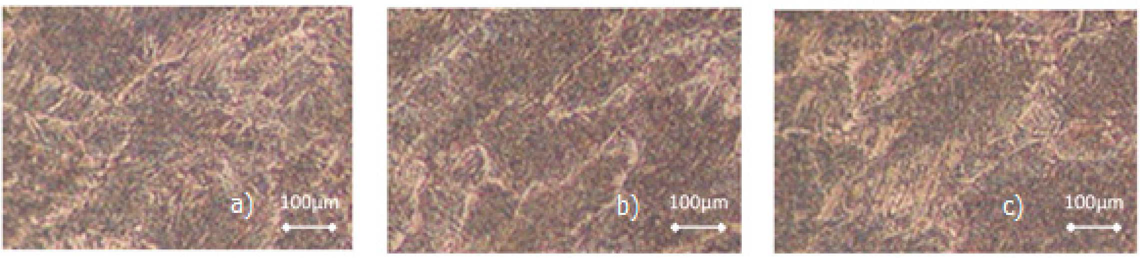

Figure 2. Acicular ferrite above 60 vol % in various deposits: (**a**) argon micro-jet cooling on the left, (**b**) helium micro-jet cooling in the middle, (**c**) gas mixture (90 vol % argon-10 vol % carbon dioxide) for micro-jet cooling on the right.

The next part of the research concentrated on impact toughness tests (Charpy V-notch test, average of five samples) and the results are presented in Table 5.

Table 5. Impact toughness of the WMD after MAG welding with various micro-jet gases.

Micro-Jet Gas or Mixture	Temp (°C)	Impact Toughness (KV, J)
Without cooling	−40	below 47
Ar	−40	68
He	−40	51
Air	−40	below 47
90% argon-10% carbon dioxide	−40	56
90% argon-10% helium	−40	53
90% argon-10% air	−40	below 47 [1]

[1] Own research.

It was possible to deduce that the impact toughness at negative temperatures of the weld metal deposit was apparently affected by the type of micro-jet gases (or mixtures) in the cooling injector. Only argon, helium, and two gas mixtures of 90 vol % argon-10 vol % carbon dioxide and 90 vol % argon-10 vol % helium were regarded as a good choice for MAG welding. Weld metal deposits received after welding with micro-jet cooling could have impact toughness class (minimum 47 J at −40 °C). Responsible structures should also be tested for impact toughness at low temperatures, as many European countries have winter temperatures of −40 °C, which are dangerous for construction. After the impact toughness analysis, a fractography test was conducted. Fractographic methods are routinely used to determine the cause of failure in engineering structures. Figure 3 presents a typical fracture of the WMD after welding with micro-jet cooling (Scanning Electron Microscope, Hitachi, Silesian University of Technology, Katowice, Poland).

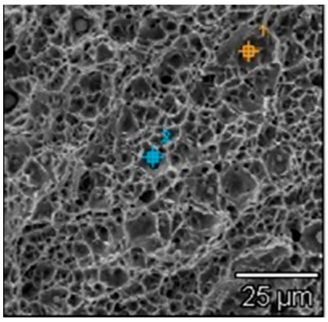

Figure 3. Scanning electron micrograph of small-sized inclusions in the WMD after welding with argon micro-jet cooling.

A small percentage of small inclusions (in the range of 0.3–0.6 µm) that are beneficial for acicular ferrite formation in welding conditions was also observed in the analysis [5,6,29] (Table 6).

Table 6. Percentage of small inclusions (0.3–0.6 µm) in the WMD.

Micro-Jet Gas or Mixture	Percentage of Inclusions, 0.3–0.6 µm
Without cooling	53
Ar	75
He	63
Air	56
90 vol % argon-10 vol % carbon dioxide	67
90 vol % argon-10 vol % helium	68
90 vol % argon-10 vol % air	61 [1]

[1] Own research.

It was possible to deduce that the size of the non-metallic inclusions depended on the type of gas or mixture used in the micro-jet cooling. This is very important, as only small inclusions (oxide/sulfide/silicate/nitrite) are beneficial for acicular ferrite formation in welding conditions [5,6].

4. Discussion

Micro-jet cooling technology can be considered as an innovative way to steer metallographic structure just after steel welding. Due to this process, it is possible to obtain a very high amount of acicular ferrite (above 65%) in the WMD which is unavailable in standard welding methods. In this study, the WMD was prepared by the MAG process with micro-jet cooling with varied tested gases and mixtures. The thermal conductivity of various gases and gas mixtures used for the tests influenced different metallographic structures, respectively. The amount of acicular ferrite in the WMD was strongly dependent on the kind and size of the non-metallic inclusions within it, and the research showed a correlation between the non-metallic inclusions and micro-jet cooling parameters. This is very important, as only the small inclusions (oxide/sulfide/silicate/nitrite) are beneficial for acicular ferrite formation in welding conditions. Furthermore, further tests should be connected with the modification of other micro-jet cooling parameters. According to the literature, the impact toughness of the WMD after welding was approximately 20% lower, especially at negative temperatures. According to References [2,5], beneficial small inclusions (about 0.4 μm) was also obtainable.

5. Conclusions

In summation, it was possible to show that the MAG process connected with micro-jet cooling was tested with great success. It was especially observed that argon, helium, and some gas mixtures (90 vol % argon-10 vol % carbon dioxide, 90 vol % argon-10 vol % helium) were very beneficial for micro-jet cooling just after MAG welding. It was also possible to obtain a much higher amount of acicular ferrite and a better impact toughness of welds. The preliminary results showed the validity of the theoretical assumptions, and thus the applicability of this technology in industry.

On the basis of this investigation, it is possible to conclude that:

- Micro-jet-cooling can be considered as an important element of the MAG process;
- Micro-jet-cooling after welding can seriously improve the amount of acicular ferrite;
- Micro-jet cooling can guarantee a greater percentage of small non-metallic inclusions that are beneficial for austenite–acicular ferrite conversion; and
- Micro-jet cooling can guarantee good impact toughness at negative temperature of welds (fourth impact toughness class), respectively.

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Author Contributions: Bożena Szczucka-Lasota and Tomasz Węgrzyn created Sections 1–3; Bożena Gajdzik and Łukasz Wszołek analyzed the data; Bożena Gajdzik and Łukasz Wszołek contributed to the analysis of welding with micro-jet cooling with bibliographic material; Bozena Szczucka-Lasota and Bożena Gajdzik established the conclusions; and Bożena Szczucka-Lasota and Tomasz Węgrzyn wrote the paper.

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