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Original scientific paper

The influence of the oxygen equivalent in a gas-mixture on the structure and toughness of microalloyed steel weldments

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Abstract: Testings were carried out on two steels. The first was microalloyed with Nb and second with Ti, Nb and V. The impact toughness of weld metals of these steels was evaluated using an instrumented Charpy pendulum. Five different gas mixtures (Ar, CO_2, O_2) were used to determine the optimal gas shielded metal arc process for both steels. The oxygen equivalent was used as a representative parameter of a mixture to follow, in particularly, its effect on the microstructure, toughness and crack propagation energy of the weld metal. For these investigated steels, the optimum gas mixture was established (5 % CO_2, 0.91 % O_2, balance Ar), which provided the maximum crack propagation energy, due to the microstructure which consisted dominantly of acicular ferrite.

Keywords: oxygen equivalent, toughness, microalloyed steel, gas mixture, fracture.

INTRODUCTION

Welding by the metal arc process with a mixture of shielding gases has been increasingly popular in recent years. Mixtures of argon (Ar), carbon dioxide (CO_2), and/or oxygen (O_2) are often used for the welding of microalloyed steels. The composition of the gas mixture significantly affects the weldment properties, especially the weld metal toughness. Namely, increasing the presence of oxide inclusions in a weld metal, at least to a certain extent, promotes nucleation of acicular ferrite, which is well-known for its beneficial effect on both the weld metal toughness and strength.[1] This effect has been investigated through the so-called oxygen equivalent (O_{eq}), introduced according to empirical formulas available in the literature.[2] The oxygen equivalent indicates the effect of oxygen on microstructure and toughness of a weld metal.

The importance of impact toughness has been significantly increased after the introduction of the instrumented Charpy pendulum, *i.e.*, after the application of an oscilloscope enabled the separation of the total impact energy into crack initiation

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TABLE I. Composition of base and filler metals

Element	C	Si	Mn	P	S	Cu	Al	Nb	Ti	Cr	Ni	V
Steel N	0.07	0.15	0.66	0.016	0.010	0.13	0.092	0.077	–	0.042	0.036	–
Steel T	0.056	0.32	1.28	0.012	0.005	0.031	0.049	0.045	0.02	–	–	0.054
VAC60 Ni	0.08–0.1	–	1.4–1.6	P+S<0.025		–	–	–	–	–	1–1.2	–

and crack propagation energy: $E_u = E_{inc} + E_{lom}$, where E_u denotes the total impact energy, E_{inc} the crack initiation energy and E_{lom} the crack propagation energy. Even if two materials exhibit he same toughness value, *i.e.*, total impact energy, their behavior can be different from the point of view of crack initiation and propagation. For example, although the total impact energy may surpass the critical value, the initiation energy may be dominant, leaving only a small contribution for the propagation energy. In such a case, the value of the total energy is in itself not enough to guarantee the avoidance of catastrophic fracture.[3] Thus, if a crack already exists, which is a reasonable assumption for many welded joints,[4] the critical toughness value should take into account only the crack propagation energy. Hence, different values of the critical toughness, from 28 J,[5–7] to 35 J[1] and 40 J,[8] specifically for microalloyed steels, can be found in the literature.

Therefore, the influence of the gas mixture on the microstructure, toughness and propagation energy, in particular, of the weld metal has been investigated for two hot-rolled microalloyed steels, welded by the metal arc process with five different mixtures of shielding gases, comprising Ar, CO_2 and O_2.

EXPERIMENTAL

Two microalloyed steels (hot rolled plates) were used for welding, one alloyed with Nb (denoted as N steel) of thickness 11 mm, and the other one alloyed with Nb, V and Ti (denoted as T steel) of thickness 7.2 mm. The compositions of both steels are given in Table I.

Welding was performed by metal arc process with five different shielded gas mixtures, as shown in Table II. The filler material, was commercially available electrode wire VAC 60 Ni, (made by "Jesenice" – Slovenia), which has the classification G3Ni1, according to EN 440, SG-2 according to DIN 8559 and ER 80 S-Ni1 according to ASME/AWS 5.28. Its composition is also given in Table I. Preheating was not applied, since the *C* equivalent was $CE = 0.20$ (N steel), and $CE = 0.34$ (T steel). (using the relation $CE = C + \frac{\text{Mn}}{6} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} + \frac{\text{Ni} + \text{Cu}}{15}$)

TABLE II. Chemical composition of the gas mixture and their oxygen equivalent

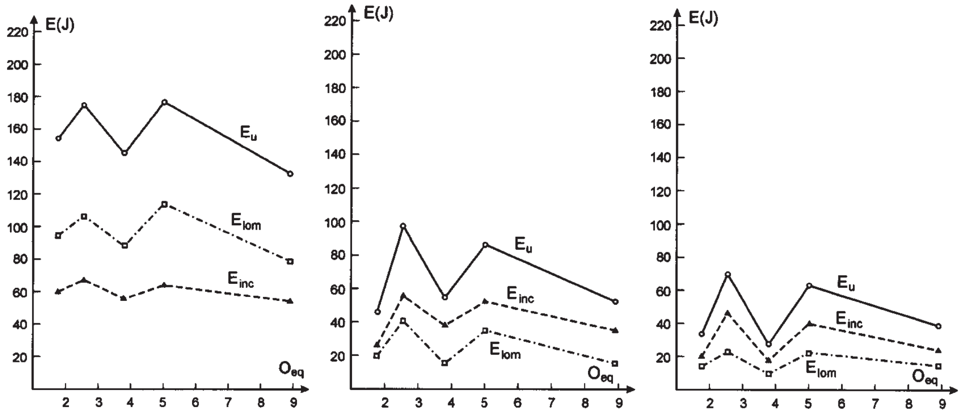
No. of mixture	Volume content/vol %			Oxygen equivalent, O_{eq}*
	CO_2	O_2	Ar	
1	5.24	–	Balance	1.76
2	5.00	0.91	Balance	2.54
3	4.70	2.30	Balance	3.78
4	10.30	–	Balance	5.09
5	14.80	–	Balance	8.90

* $O_{eq} = -0.088 + 0.148\,[CO_2]^{1.524} + [O_2]$, where $[CO_2]$ and $[O_2]$ are volume contents[1]

The input energy was kept in a narrow range 7–9 kJ/cm (using the formula $Q = \frac{60UI}{V}\eta\, 10^3$) to exclude its influence since the weld metal toughness has been shown to be sensitive to input energy for both steels.[9] Coupon plates with V grooves of both steels were welded and used for testing. The specimens for weld metal toughnees testing were cut out, with dimensions in accordance with their thickness: 55×10×9 mm for the N steel, 55×10×6 mm for the T steel. A standard 2 mm deep V notch was machined along the 10 mm dimension. A Charpy instrumented machine capacity of 300 J was used. Since the instrumented Charpy testing has not yet been standardized, the experimentally verified recommendations, prescribed by ESIS,[10] were used instead. Testing was performed at room temperature (20 ºC), and at two temperatures below zero, –40 ºC and –55 ºC.

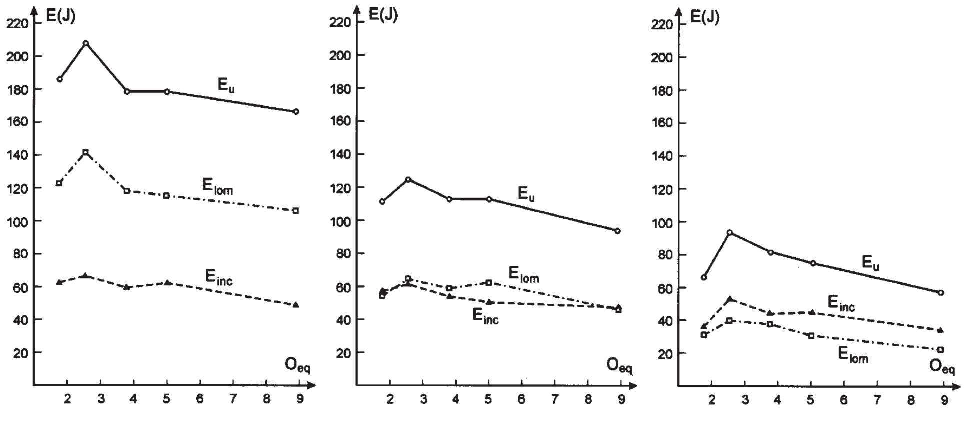
RESULTS AND DISCUSSION

The obtained energies were scaled to the standard thickness of 10 mm. The dependence of the toughness on the oxygen equivalent is shown in Fig. 1 for the N steel and in Fig. 2 for the T steel. The dependence of the weld metal toughness on the testing temperature for both steels, is shown in Figure 3, for each gas mixture separately.



a) T=+20°C b) T= - 40°C c) T= -55°C

Fig. 1. Total energy (E_u), initation energy (E_{inc}) and propagation energy (E_{lom}) *vs.* oxygen equivalent for steel N at different temperatures.

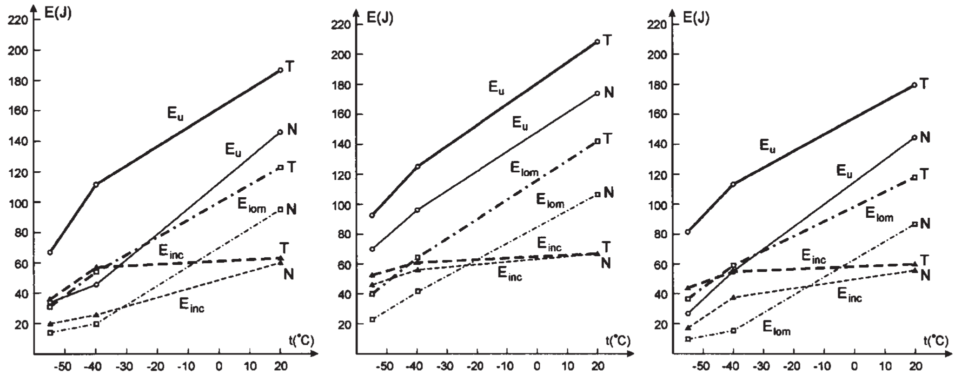


a) T=+20°C b) T= -40°C c) T= -55°C

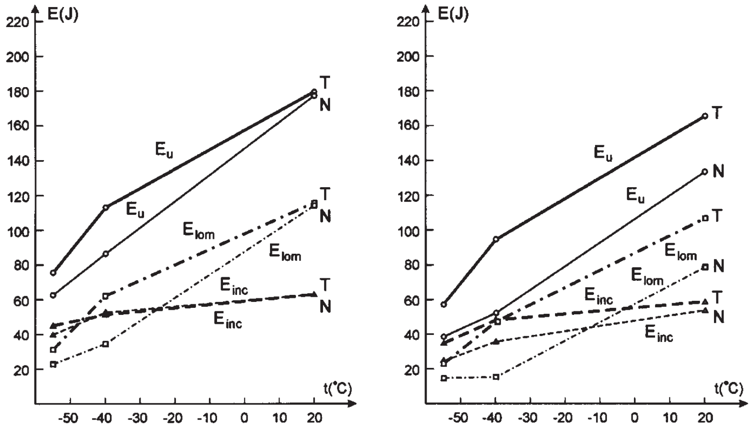
Fig. 2. Total energy (E_u), initiation energy (E_{inc}) and propagation energy (E_{lom}) *vs.* oxygen equivalent for steel T at different temperatures.

The total impact energy for both weld metals at room temperature was exceptionally high, as well as the crack propagation energy, which was much higher than the initiation energy, as can be seen in Figs. 1a and 2a. The initiation energy of the welded joints of steel T changed little with temperature down to –40 °C, when it decreases significantly (Fig. 3). The initiation energy for the welded joints of steel N behaved similarly, except for gas mixture 1, where the significant drop was noticeable at –40 °C (Fig. 3a). For both steels, at all testing temperatures, the initiation energy was highest for mixture 2, *i.e.*, for O_{eq} = 2.54 vol.%, indicating the existence of the optimal gas mixture composition. For steel N, drop in all energy values for gas mixture 3 which was not further analysed, can be seen.

The propagation energy was high at room temperature (min. 79 J for steel N



a) gas mixture 1 b) gas mixture 2 c) gas mixture 3



d) gas mixture 4 e) gas mixture 5

Fig. 3. Total energy(E_u), initiation energy (E_{inc}) and propagation energy (E_{lom}) *vs.* temperature for different gas mixtures.

and 107 J for steel T), but it was significantly smaller at the lower testing temperatures (Fig. 3). The propagation energy for both steels was higher than the initiation energy at room temperature for all gas mixtures. At –40 ºC, the propagation energy for steel N became lower than the initiation energy; this trend was even more expressed at –55 ºC. For steel T, this phenomenon occurred at –55 ºC, and even then the values of the propagation energy were relatively high, at least for gas mixtures 1–3, with a minimum values above 30 J.

Since crack appearance in welded joints must not be neglected,[4] the criterion of a minimal total impact energy is not reliable, even if higher energies (35 or 40 J) are required, as is often recommended for microalloyed steels.[1,8] Thus, a more reliable criterion for microalloyed steels would be the recommendation of a high minimal value, *e.g.* 40 J, of the propagation energy. For steel N at – 40 ºC, only gas mixture 2 satisfies this criterion, whereas at –55 ºC, even this mixture is not acceptable (Fig. 3b). For steel T at –40 ºC, all gas mixtures satisfy this criterion and at –55 ºC gas mixture 2 is acceptable, while mixtures 1 and 3 would be acceptable with a criterion 30 J (Fig. 3a–c).

Fig. 4. Nucleation of AF on oxide inclusions.[12]

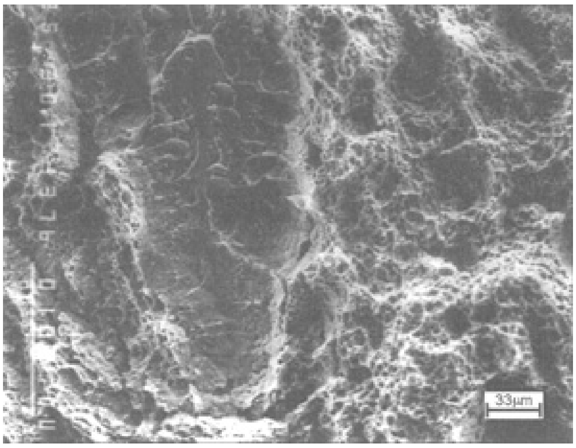


Fig. 5. Mixed fracture: ductile and brittle transgranular.

The reason for higher propagation energy is the presence of acicular ferrite (AF).[11] Increasing the oxygen content in a gas mixture increases the number of inclusion sites and, thus, the number of acicular ferrite nucleation sites, Fig. 4, but only up to a certain limit. Above that limit, the opposite effect is noticeable, namely the AF content is reduced due to the increased content of other ferrite morphologies, such as ferrite with a secondary phase (FS) and proeutectoid ferrite (PF).[12,13] For higher oxygen contents, PF has a typical course microstructure, appearing in blocks.[1] The microstructure of the two steels tested in this study consists of AF, PF and FS, the contents of which are highly dependent on the gas mixture composition, *i.e.*, on the oxygen content, as was shown previously.[12] The highest content of

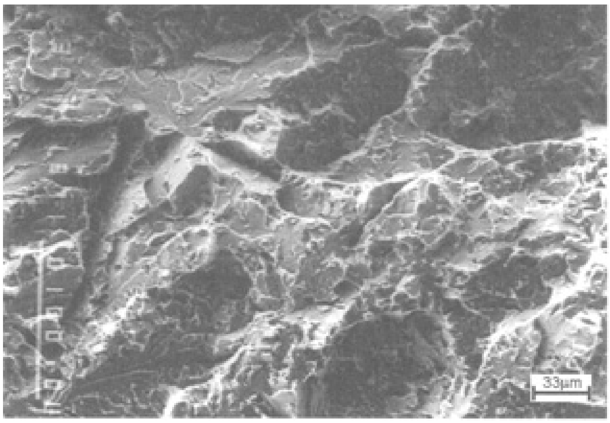


Fig. 6. Brittle fracture at –40 ºC; transgranular and intergranular (steel N).

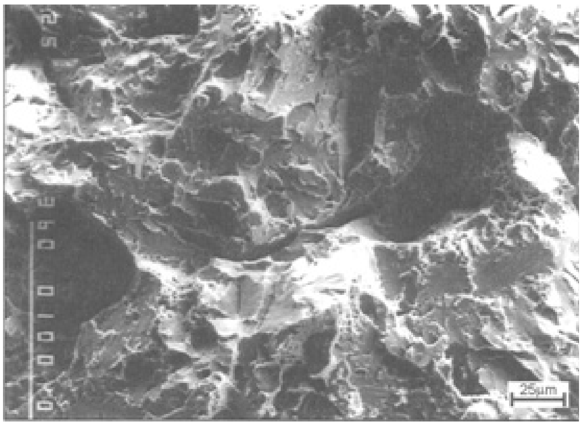


Fig. 7. Brittle fracture at –55 ºC, dominantly intergranular (steel T).

AF corresponds to the gas mixture 2 for both steels, which is in accordance with the highest toughness also being obtained with gas mixture 2.

Fractographic investigation of the Charpy specimens indicated the same type of fracture at one temperature, regardless of the gas mixture, in accordance with force deflection diagrams previoundy obtained on a Charpy instrumented pendulum.[12] At room temperature, ductile transgranular fracture is dominant, with a small amount of brittle transgranular fracture, Fig. 5. At lower temperatures, the amount of brittle fracture is increased, as is to be expected due to the reduced propagation energy. Intergranular fracture becomes dominant for steel N and – 40 ºC, Fig. 6, whereas the same phenomenon occurs at –55 ºC for steel T, Fig. 7. This is in agreement with the measured energy values, indicating that brittle fracture becomes dominant when the propagation energy becomes smaller than the initiation energy.

Bearing in mind that transgranular fracture involves cleavage in certain planes, while intergranular fracture develops due to brittle phases on grain boundaries or due to soluted atoms in the vicinity,[14] it is obvious why intergranular fracture appears at – 40 ºC for steel N and at –55 ºC for steel T. Namely, the microstructure of steel N weld metal has a higher content of PF and FS, initiated on austenite boundaries and grown toward the grain interior.[15,16] Since both PF and FS are brittle, their increased content obviously reduces the toughness of a steel.

CONCLUSIONS

Based on the analysis of the experimental results, the following conclusions can be deduced:

– Increasing the oxygen equivalent is beneficial for weld metal toughness (total impact energy), but only to a certain limit, after which it becomes detrimental. The same holds for the propagation and initiation energies, the effect being more pronounced for the former one. The reason for this is the presence of acicular ferrite, nucleated at oxide inclusions.

– The propagation energy for steel N and – 40 ºC is sufficient only with gas mixture 2, while no mixtures provided a sufficiently tough weld metal at –55 ºC. Steel T has a significantly better toughness, since all mixtures resulted in a sufficient propagation energy at –40 ºC and even at –55 ºC gas mixture 2 resulted in a weld metal with satisfactory toughness.

– Fractography of Charpy specimens indicates an increase in intergranular brittle fracture with decreasing temperature, in complete accordance with the obtained energy values. The reduced energy values are a consequence of the increased content of PF and FS, as brittle microstructures.

ИЗВОД

УТИЦАЈ ЕКВИВАЛЕНТНОГ САДРЖАЈА КИСЕОНИКА У МЕШАВИНИ ГАСОВА НА СТРУКТУРУ И ЖИЛАВОСТ МЕТАЛА ШАВА МИКРОЛЕГИРАНИХ ЧЕЛИКА

РАДИЦА ПРОКИЋ-ЦВЕТКОВИЋ, АНЂЕЛКА МИЛОСАВЉЕВИЋ, АЛКСАНДАР СЕДМАК И ОЛИВЕРА ПОПОВИЋ

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Испитивања су изведена на два челика. Први је микролегиран са Nb, а други са: Ti, Nb и V. Жилавост метала шава наведених челика је одређена на инструментираном Шарпијевом клатну. Пет различитих мешавина гасова (Ar, CO_2, O_2) је употребљено за одређивање оптималне заштитне атмосфере при заваривању испитиваних челика. Еквивалентни садржај кисеоника је узет као параметар мешавине и установљен је његов утицај на микроструктуру метала шава, жилавост и енергију раста прслине. За оба челика, као оптимална мешавина гасова се показала (5 % CO_2, 0.91 % O_2, остатак Ar), која обезбеђује максималну енергију раста прслине, као и доминантну микроструктуру ацикуларног ферита.

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