МАТЕРІАЛОЗНАВСТВО

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INFLUENCE OF STRUCTURAL PARAMETERS OF LOW-CARBON STEEL ON ELECTRIC ARC BURNING

Purpose. The article is aimed to evaluate the influence of structural parameters of low-carbon steel on arcing process. **Methodology.** The values of the micro- and substructure characteristics of the electrode wire metal were changed by varying the parameters of heat treatment and cold deformation by drawing. The degree of plastic deformation was obtained by drawing blanks from different initial diameter to final dimension of 1 mm. The thermal treatment was carried out in electric chamber furnace of the SNOL-1,6.2,5.1/11-IZ type. The temperature was measured by chromel-alumel thermocouple and the electromotive force was determined using the DC potentiometer. In order to obtain the substructure of different dispersion degree the steel (after quenching from temperatures and tempering at 650°C for 1 hour) was subjected to cold drawing to reduction 17 – 80%. To form structure with different ferrite grain size the steel after drawing was annealed at 680°C for 1 hour. The microstructure was examined under a light and electron transmission microscope UEMV-100K at the accelerating voltage 100 kV. The grain and subgrain sizes were evaluated using the methodologies of quantitative metallography. A welding converter of the PSG-500 type was used to study the arc welding process of direct and reverse polarities. **Findings.** The experimentally detected value of the welding current, which depends on the degree of deformation during wire drawing, under conditions of stable arc burning of direct polarity is about an order of magnitude lower than the calculated value. Similar difference was found for the arc of reverse polarity: the experimental value of the welding current is 5–6 times less than the calculated value. Dependence analysis shows that, regardless of the polarity of the welding arc, a good enough agreement between the calculated and experimental values of the welding current is limited to deformations of 60%. For deformation degrees of more than 60%, the differences are explained by qualitative changes in the dislocation cell structure. **Originality.** In the conditions of stable arcing of different polarity for the electrode of low-carbon steel, an extreme dependence of welding current on the degree of cold plastic deformation was observed. **Practical value.** Influence of ferrite grain size of electrode wire on the value of welding current is much greater than that from substructure presence.

Keywords: structure; welding electric current; polarity; welding arc stability; cold plastic deformation; cell; ferrite

Introduction

In conditions of electric arc welding the process of arcing is sensitive to the influence of a certain number of factors [7, 11, 12, 18]. They include maintaining the optimal ratio between the rate of the electrode metal melting and its feeding into reaction zone, conditions of metal transfer through the interelectrode space [8, 15-17, 19, 20], etc. Taking into account that metal transfer between the

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electrodes is carried out in the form of a gas-droplet mixture, the very process of liquid metal droplet formation at the end of the electrode, its size and shape should to some extent influence the technological characteristics of electric arc welding. Analysis of the conditions for formation of liquid metal droplet indicates existence of certain relationship between the surface tension of metal and gravitational component [9]. Taking into account possible dependence of the surface tension forces on the structural state of electrode metal, the size of structural elements may have certain influence on the conditions of formation and burning of electric arc.

Purpose

The article is aimed to evaluate the influence of structural parameters of low-carbon steel on arcing process.

Material and methodology of study

A wire of 1 mm diameter of low-carbon steel with a carbon content of 0.2% was used as a material for electrode. The values of the micro- and substructure characteristics of the electrode wire metal were varied by varying the parameters of heat treatment and cold deformation by drawing. The values of the micro- and substructure characteristics of the electrode wire metal were changed by varying the parameters of heat treatment and cold deformation by drawing. The degree of plastic deformation was obtained by drawing blanks from different initial diameter to final dimension of 1 mm. Thermal treatment was carried out in electric chamber furnace of the SNOL-1,6.2,5.1/11-IZ type. To prevent the formation of oxide film on the metal surface, the samples were placed in quartz glass ampoules with preliminary deairing to the level of forvacuum. The temperature was measured by chromel-alumel thermocouple and the electromotive force was determined using the DC potentiometer. In order to obtain the substructure of different dispersion degree the steel after quenching from temperatures Ac_3 and tempering at 650°C for 1 hour was subjected to cold drawing to reduction 17–80%. To form structure with different ferrite grain size the steel after drawing was annealed at 680°C for 1 hour. The microstructure was examined under a light and electron transmission microscope UEMV–100K at the accelerating voltage 100 kV. The grain and subgrain sizes were evaluated using the methodologies of quantitative metallography [5]. A welding converter of the PSG-500 type was used to study the arc welding process of direct and reverse polarities. The welding current value was estimated as the average of 10 measurements.

Findings

Analysis of the results of investigations [7–9] indicates that when metal is melting, the surface tension forces form a drop at the end of the electrode. The moment of droplet detachment corresponds to the condition that the gravitational component exceeds the surface tension force. Taking into account that as the molten metal temperature rises, the surface tension force decreases, the welding current increase should lead to the dispersion of the emerging droplets. Condition of balance between the hydrostatic pressure from pinch effect and the surface tension (σ) makes it possible to estimate the critical value of welding current (($I_k = B\sqrt{\sigma \cdot d}$, where B – is a constant equal to 32.7 $\text{A/dynes}^{0,5}$, d – the electrode diameter) upon the detachment of liquid metal droplet [9]. Substituting the constant B and σ of molten metal (1220 dynes/cm [9]) in the ratio for I_k, the value I_k for low-carbon steel should be about $360\,A$, which is confirmed by the data [8, 9]. The experimentally observed value of the welding current (I_1) on the degree of deformation during wire drawing (ε) under conditions of stable arcing of direct polarity, is approximately an order of magnitude lower than the calculated value (Fig. 1). A similar difference was found for the arc of reverse polarity: I_1 less than the calculated one in 5–6 times.

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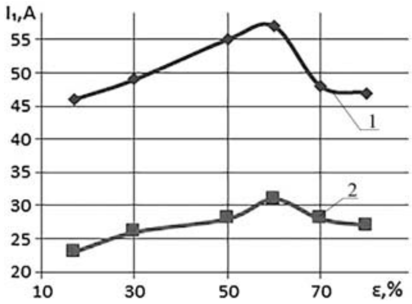


Fig. 1. Influence of the plastic deformation degree by drawing on the welding current value (I_1):
1 – reverse polarity arc; *2* – direct polarity arc

The extreme nature of I_1 dependence on ε, is apparently due to the peculiarities of the substructural metallic structure. Considering the nature of dependence for I_k, one can formally assume that either the value *B* depends on the chemical composition or structure of the steel, or σ should be replaced by another characteristic. To explain the correlation ratio I_1 on ε (Fig. 1), it was made an attempt to replace σ by the metal surface tension coefficient in the solid state. Taking into account the presence of volume fraction of ferrite in the investigated steel around 97–98%, the ferrite surface tension coefficient (σ_F) can be taken as σ. Using the experimental data [2] and the transformations carried out [14], for a cold-deformed state one can write:

$$\sigma_F = {G \cdot b^2}/{2D}, \qquad (1)$$

where G – ferrite shear modulus (0.82 dynes/cm^2), b – Burgers vector $2{,}3 \cdot 10^{-8}$ sm [1], D – size of dislocation cell.

Refinement of the dislocation cell structure obeys a proportional dependence on the degree of cold plastic deformation.

Taking into account that 20–30% of reduction is enough to start the formation of dislocation cellular structure of various degrees of perfection (Fig. 2), determination of the dependence of D on ε made it possible to calculate the welding current value (I_D).

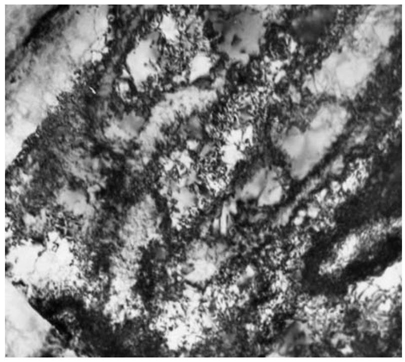
As a ratio the dependence for I_k after an appropriate substitution of σ for σ_F was used:

$$I_D = B \cdot \sqrt{\sigma_F d} \qquad (2)$$

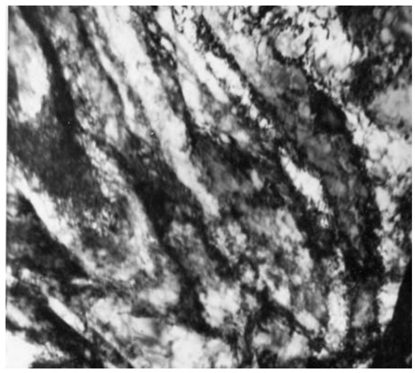
A joint analysis of absolute values I_D and I_1 (Fig. 3) for direct polarity arc indicates a fairly good correlation only up to 60%reduction. For deformation degrees of more than 60%, the observed differences can only be explained by qualitative changes in the dislocation cell structure.

Indeed, at reductions more than 60–70% in carbon steels the processes of perfecting the formed dislocation cells start to develop.

At high degrees of plastic deformation, a progressive increase in the dislocation density is accompanied by intensive cleansing of the cell body from unbound dislocations, changes in the form of cells, decrease in thickness of subboundaries, and so on. [1, 4, 13]. All this, apparently leads to violation of the ratio for σ_F and is inherited by calculations I_D. The results obtained for reverse polarity arc are similar to the data for direct polarity arc.



а – a



б – b

Fig. 2. Structure of steel 20 after martensite quenching, tempering at 650 °C, cold drawing on 17 (a) and 30 % (b)

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With constant sub-structural parameters of cold-deformed steel, for the arc of direct and reverse polarity, the nature of relationships $I_1 = f(\varepsilon)$ (Fig. 1) indicates possible change in the coefficient *B* depending on the arc polarity. Taking into account existence of certain difficulties in burning an arc of reverse polarity, a change of value *B* can be fully justified. Indeed, when the polarity reverses, the conditions for stable arc burning should become more complicated [7, 8]. The evaluation showed that in order to increase the degree of coincidence between the calculated and experimental values of the welding current, for the reverse polarity arc, the value *B* should be about twice as large as for the direct polarity arc. The result of electric current calculating for the reverse polarity arc with respect to relation (2) (will be denoted as I_D^*) is shown in the Fig. 3.

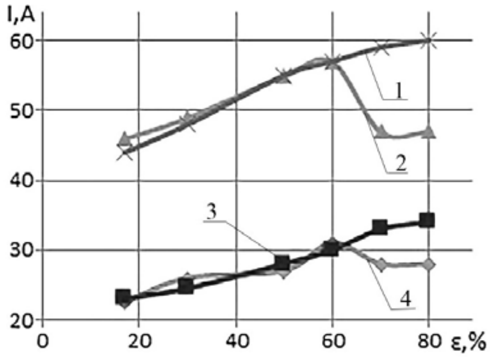

Fig. 3. The influence of deformation degree by drawing the steel 20 on the welding current when burning the arc of direct (3, 4) and reverse (1, 2) polarity:

2, 4 – current curves I_1 obtained experimentally;

1, 3 – curves of currents, I_D^* and I_D respectively calculated according to the relation (2)

Dependence analysis shows that, regardless of the welding arc polarity, a good enough agreement between the calculated and experimental values of the welding current is limited to deformations of 60%. For large reductions, the degree of mismatch is proportional to the level of welding current values. For the direct polarity arc, when the welding current level is 20–35, the deviation of calculated values (I_D) from I_1 is 12–14%. For the reverse polarity arc at I_1 = 45–57 A, the value of difference between I_D^* and I_1 reaches 20%. Results of the study indicate the existence of a certain influence of substructural metallic structure of the electrode metal on the welding arc burning processes. The observed dependence of the electric current value when burning the arc of different polarity is sufficiently well explained by the parameters of the substructure of cold-deformed low-carbon steel before the appearance of qualitative changes in the internal structure of metal.

In order to explain the nature of the observed welding current dependence on the substructure parameters of cold-drawn metal, investigations were carried out on the influence of ferrite grain boundaries of with large disorientation angles (d_f - is the ferrite grain size after annealing the cold-drawn metal). Such necessity is due to differences in the degree of accumulation and distribution of crystal structure defects from the reduction value when drawing and after development of recrystallization processes when annealing. Taking into account the inverse proportional relationship between the ferrite subgrain size (D) on the reduction degree when drawing [6] and the observed correlation relationship $I_1 = f(\varepsilon)$ (Fig. 3), it can be assumed that to describe the dependence $I_1 \approx f(d)$ the relationship of the following type can be used:

$$I = A + k \cdot D^n, \qquad (3)$$

where *A, k* and *n* – are the constants.

Results of the construction I_1 on $(d_0)^{-0,5}$, where d_0 – ferrite grain size of the steel are shown in the Fig. 4.

The analysis of the ratios indicates a fairly good correlation when using the dependence:

$$I_1 = I_i + kd_0^{-0,5}, \qquad (4)$$

where I_i – is the welding current at $d_0 \to \infty$, *k* – is the angle coefficient.

In general, it should be noted that regardless of the type of interface, increase in their total length is accompanied by increase in the welding current value. Taking into account qualitative differences in the distribution nature of crystal structure defects during the formation of grain boundaries with large disorientation angles and sub-grains as a result of cold drawing [4, 6], the existence of sepa-

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rate dependences for d_f and D is completely justified.

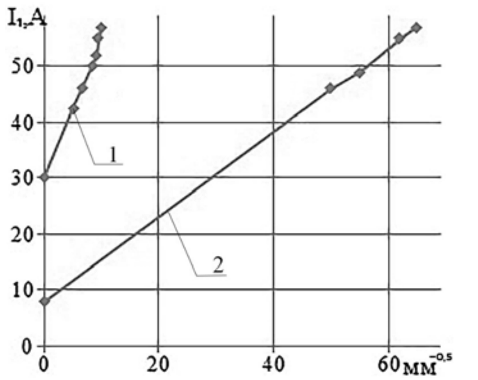

Fig. 4. Influence of the grain sizes (1) and the ferrite subgrain (2) of steel 20 on the welding current when burning the arc of reverse polarity

Analysis of the absolute values of the parameters of equation (4) indicates that the influence of the presence of ferrite grain boundaries with large disorientation angles (I_i=30 A, k = 2 A/mm^{1,5}) in the steel structure is much greater than the influence of the subgrain structure (I_i= 8 A, k = 0,75 A/mm^{1,5}). On the other hand, the electric resistance value for the ferrite structure of low-carbon steels is proportional to the accumulated defect density of the crystal structure [3] and inversely proportional to the ferrite grain size [10], can to some extent exert its influence on the process of welding arc burning through the surface tension of the metal.

Conclusions

1. In the conditions of stable burning of the arc of different polarity for the low-carbon steel electrode, the extreme dependence of the welding current on the degree of cold plastic deformation was observed.
2. Influence of the ferrite grain size of the electrode wire on the welding current value is much greater than the effect of the substructure presence.

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ВПЛИВ СТРУКТУРНИХ ПАРАМЕТРІВ НИЗЬКОВУГЛЕЦЕВОЇ СТАЛІ НА ГОРІННЯ ЕЛЕКТРИЧНОЇ ДУГИ

Мета. В статті передбачається зробити оцінку впливу структурних параметрів низьковуглецевої сталі на процес горіння електричної дуги. **Методика.** Значення мікро- і субструктурних характеристик металу електродного дроту змінювали, варіюючи параметрами термічної обробки та холодної деформації волочінням. Ступінь пластичної деформації отримували волочінням заготовок різного вихідного діаметра на кінцевий розмір 1 мм. Термічну обробку здійснювали в електричній камерній печі типу СНОЛ-1,6.2,5.1/11-3. Температуру вимірювали термопарою хромель-алюмель із визначенням електрорушійної сили за потенціометром постійного струму. Для отримання субструктури різної дисперсності сталь (після загартування й відпускання температури до 650 °С протягом 1 години) піддавали холодному волочінню на обтиск до 17–80 %. Для формування структури з різним розміром зерна фериту сталь після волочіння піддавалася відпалу при 680 С протягом 1 години. Мікроструктуру досліджували під світловим електронним просвітчастим мікроскопом УЕМВ-100К при прискорюючій напрузі 100 кВ. Розмір зерна і субзерна оцінювали з використанням методик кількісної металографії. Для досліджень процесу горіння зварювальної дуги прямої та зворотної полярностей використовували зварювальний перетворювач типу ПСГ-500**.** **Результати.** Експериментально виявлене значення зварювального струму, що залежить від ступеня деформації при волочінні дроту, в умовах

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стабільного горіння дуги прямої полярності приблизно на порядок нижче розрахункової величини. Аналогічну відмінність виявлено й для дуги зворотної полярності: експериментальна величина зварювального струму менше розрахункової у 5–6 разів. Аналіз залежностей свідчить, що незалежно від полярності зварювальної дуги, досить гарний збіг між розрахунковими та експериментальними значеннями зварювального струму обмежується деформаціями до 60 %. Для ступенів деформації більше 60 % відмінності пояснюються якісними змінами в дислокаційній комірчастій структурі. **Наукова новизна.** В умовах стабільного горіння дуги різної полярності для електрода з низьковуглецевої сталі виявлена екстремальна залежність зварювального струму від ступеня холодної пластичної деформації. **Практична значимість.** Вплив розміру зерна фериту електродного дроту на величину зварювального струму значно перевищує ефект від присутності субструктури.

Ключові слова: структура; зварювальний електричний струм; полярність; стабільність зварювальної дуги; холодна пластична деформація; комірка; ферит

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ВЛИЯНИЕ СТРУКТУРНЫХ ПАРАМЕТРОВ НИЗКОУГЛЕРОДИСТОЙ СТАЛИ НА ГОРЕНИЕ ЭЛЕКТРИЧЕСКОЙ ДУГИ

Цель. В статье предполагается сделать оценку влияния структурных параметров низкоуглеродистой стали на процесс горения электрической дуги. **Методика.** Значения микро- и субструктурных характеристик металла электродной проволоки изменяли, варьируя параметрами термической обработки и холодной деформации волочением. Степень пластической деформации получали волочением заготовок разного исходного диаметра на конечный размер 1 мм. Термическую обработку осуществляли в электрической камерной печи типа СНОЛ-1,6.2,5.1/11-ИЗ. Температуру измеряли термопарой хромель-алюмель с определением электродвижущей силы по потенциометру постоянного тока. Для получения субструктуры разной дисперсности сталь (после закалки и отпуска температуры до 650 °С в течение 1 часа) подвергали холодному волочению на обжатие до 17–80 %. Для формирования структуры с разным размером зерна феррита сталь после волочения подвергалась отжигу при 680 °С в течение 1 часа. Микроструктуру исследовали под световым электронным просвечивающим микроскопом УЭМВ-100К при ускоряющем напряжении 100 кВ. Размер зерна и субзерна оценивали с использованием методик количественной металлографии. Для исследований процесса горения сварочной дуги прямой и обратной полярностей использовали сварочный преобразователь типа ПСГ-500. **Результаты**. Экспериментально обнаруженное значение сварочного тока, зависящего от степени деформации при волочении проволоки, в условиях стабильного горения дуги прямой полярности примерно на порядок ниже расчетной величины. Аналогичное различие обнаружено и для дуги обратной полярности: экспериментальная величина сварочного тока меньше расчетной в 5–6 раз. Анализ зависимостей свидетельствует, что независимо от полярности сварочной дуги, достаточно хорошее совпадение между расчетными и экспериментальными значениями сварочного тока ограничивается деформациями до 60 %. Для степеней деформации более 60 % различия объясняются качественными изменениями в дислокационной ячеистой структуре. **Научная новизна.** В условиях стабильного горения дуги различной полярности для электрода из низкоуглеродистой стали обнаружена экстремальная зависимость сварочного тока от степени холодной пластической деформации. **Практическая значимость**. Влияние размера зерна феррита электродной проволоки на величину сварочного тока значительно превышает эффект от присутствия субструктуры.

Ключевые слова: структура; сварочный электрический ток; полярность; стабильность сварочной дуги; холодная пластическая деформация; ячейка; феррит

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