Study of impact strength of C-Mn-Si composition metal after wire-arc additive manufacturing (WAAM)

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The results of study of impact strength of C-Mn-Si composition metal after wire-arc additive manufacturing (WAAM) are presented. It was established that destruction of the samples of such composition at the temperatures below tough-brittle transition occurs both via tough and brittle mechanisms. The samples manufactured in the direction along built-up welding are characterized by essentially lower impact strength comparing with those manufactured in vertical direction of samples cutting. Impact strength of the samples made of 09G2SA standard steel is substantially lower than for C-Mn-Si composition metal which was obtained via additive technology. Fractographic analysis of fractures for C-Mn-Si compositions manufactured via additive technology using carbon dioxide and gas mixture displays tough pit destruction type. The samples with high impact strength are characterized by forming of cleavage facets after tough crack propagation to the sample middle, what is accompanied by significant widening opposite to a notch and narrowing under a notch. The samples with low impact strength are characterized by forming of brittle fracture directly under a notch without essential sample plastic deformation. It is shown that built-up welding with partial or complete recrystallization of rolls is required for forming of cold-resistant metal structure. In this case, order of rolls location, heat input and parameters of welding conditions make the direct effect on shape, geometrical dimensions, fusion penetration and number of rolls, as well as on size and morphology of the structural components, percent relation between cast and recrystallized microstructure of seam metal. The complex of these factors finally determines structural state and cold resistance of seam metal.

Keywords: wire-arc additive manufacturing (WAAM), metal 3D printing technologies, low-carbon steel, structure, hardness, mechanical properties, impact strength.
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Introduction

In wire-arc additive manufacturing (WAAM), electric arc is used as a heat source, while solid wire is used as initial material [1-4]. Scalability and anisotropy of properties are considered as the main factors restricting industrial use of additive technologies [3, 4]. The process of wire-arc additive manufacturing has many common features with the processes of multi-pass welding by metallic electrode and welding by tungsten electrode, both in the protective gas atmosphere. Thereby the problems connected with conventional multi-pass welding, concerning dispersion of mechanical properties (and especially impact strength), are awaited to be met in additive production [4-7].

The works [1, 2, 7-11] testify that impact strength tests are often appointed as acceptance trials for structural materials. Meeting the requirements both in strength and impact strength is the principally important step for the most structural materials; unfortunately, these properties are usually mutually exclusive [11]. It is well-known that fracture toughness is noted as the key mechanical property for high-strength materials [6-12].

The process of gas metal arc welding by metallic electrode (GMAW) using electrode wire AWS ER70S-6 for creation of single-pass construction was described in the work [8], the obtained results showed that this material has high impact strength and rather plastic behaviour. It was revealed [8, 9], that the critical range of cooling rates with large volumetric part of TiO_2 inclusions in austenite composition leads to forming of needle ferrite in steel welding seams and, respectively, to decrease of dispersion of impact strength values. It was established in the work [12] during examination of mechanical properties of low-alloy silicon-manganese composition of C-Mn-Si type with ferrite-pearlite structure, that impact strength values of such composition formed via WAAM method are higher by 2 times in comparison with welded joints built-up by Sv-08G2S wire.

At the same time the authors [12-15] noted, that existence of tough-brittle (T-B) transition on the toughness temperature relationship is a fundamental feature of low-alloy steels. It is stipulated by the fact that microstructure of such steels contains mainly ferrite components (with BSC (body centered cubic) lattice. Brittle destruction of low-alloy steels, containing ferrite components with BSC lattice, occurs via trans-crystalline cleavage, i.e. quick crack propagation along the definite crystallographic planes (manly along {100} of ferrite) [13, 15]. That's why prevention of brittle destruction is the main material science condition to provide workability of low-alloy steel as structural material. Of course, the temperature which corresponds to 100 % part of tough component in the fracture, can be considered as a sufficient criterion of metal construction workability.

However, just before manufacture of reliable components, operating in the conditions of critical loads, via WAAM method [12-20] will become the main direction, more deep understanding of mechanical properties of the obtained materials for built-up of such type is required. This work is devoted to study of metal impact strength properties for low-alloy C-Mn-Si composition, which was formed in the process of wire-arc additive manufacturing. Production of the new material with for low-alloy C-Mn-Si composition and with high impact strength values at the negative temperatures via WAAM method, unlike conventional metallurgical production method, is recognized as the scientific novelty of this work.

Materials and methods of the study

Welding wire Sv-08G2S with diameter 1.2 mm according to the GOST 2246-70 was used as the main material for forming of semiproduct and the component itself. Sheet metal from 09G2SA steel (according to the GOST 19281-89), which is related to the group of low-alloy silicon-manganese structural steels, was used for comparison of material properties obtained using welding wire Sv-08G2S (C-Mn-Si composition) via additive technology. The results of comparative tests on mechanical properties and chemical composition were presented in the work [12].

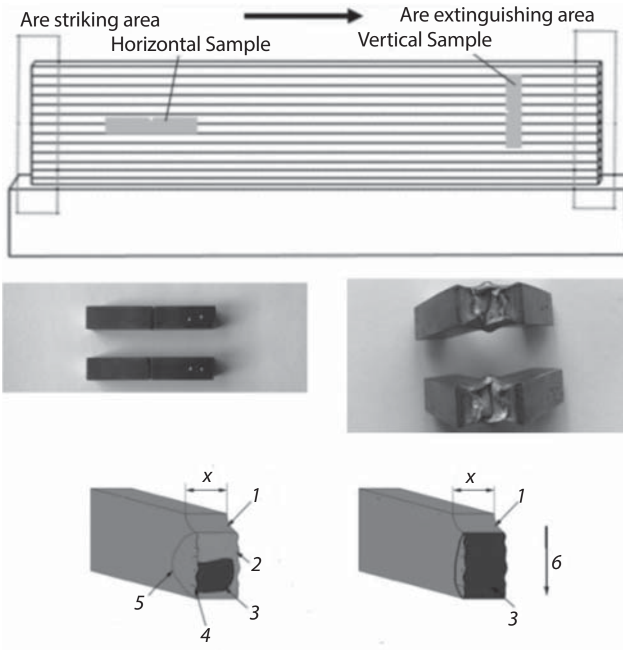


Fig. 1. The scheme of cutting the standard samples with U-shaped notch, destructed by impact bending, and determination of the relationships between tough and brittle components, plastic area, micro-cracks:
X – sample width; *1* – U-shaped notch; *2* – fracture tough component; *3* – fracture brittle component; *4* – micro-crack; *5* – plastic area; *6* – direction of the main crack

Built-up welding of wire was conducted on the steel sheet with thickness 16 mm. Semiproducts of C-Mn-Si composition with dimensions 40x50x200 mm were obtained during built-up welding. Robotic technical complex in Irkutsk National Research Technical University was used as an industrial 3D printer. This robotic technical complex includes the industrial robot KUKA KR 210 R2700 prime, the welding unit Lorch SpeedPulse S3 mobil and the balloon with protective gas CO_2 and mixture of gases ($Ar+CO_2$). Built-up welding of wire was carried out via the method of gas metal arc welding (GMAW). Each layer was formed by one roll of built-up metal during one pass.

The structure was examined for metal of formed wall using welding wire Sv-08G2S and the results were compared with the structure of strip from conventional 09G2SA steel. Microscope MicroMed2, digital microscope Olympus GX41 A (with magnification x50, x100, x200, x500 and x1000) were used for microstructure examination. Electronic microscopic researches were carried out using electronic microscope JIB-4501 JEOL. Impact strength (KCU) of the metal formed via additive technology was determined during the tests for impact bending of the samples with U-shaped concentrator according to the GOST9454-78 and GOST 6impact bending of the samples with U-shaped concentrator according to the GOST9454-78 and GOST 6996-66. The testing for impact bending was conducted on standard nominally identical samples 10x10x55 mm with U-shaped notch for strengthening of sensitivity relating to the local microstructural features of impact strength within the range T-B transition [13-15]. The samples were cut from the middle part of the built-up wall in direction of built-up movement and in perpendicular direction in the vertical plane (**Fig. 1**). The tests were conducted at the temperatures from -60 °C to +20 °C with the interval 20 °C. The results of testing were processed statistically with calculation of the confidence range as deviation from the average value, with probability $\gamma = 0.95$ according to the Student distribution law.

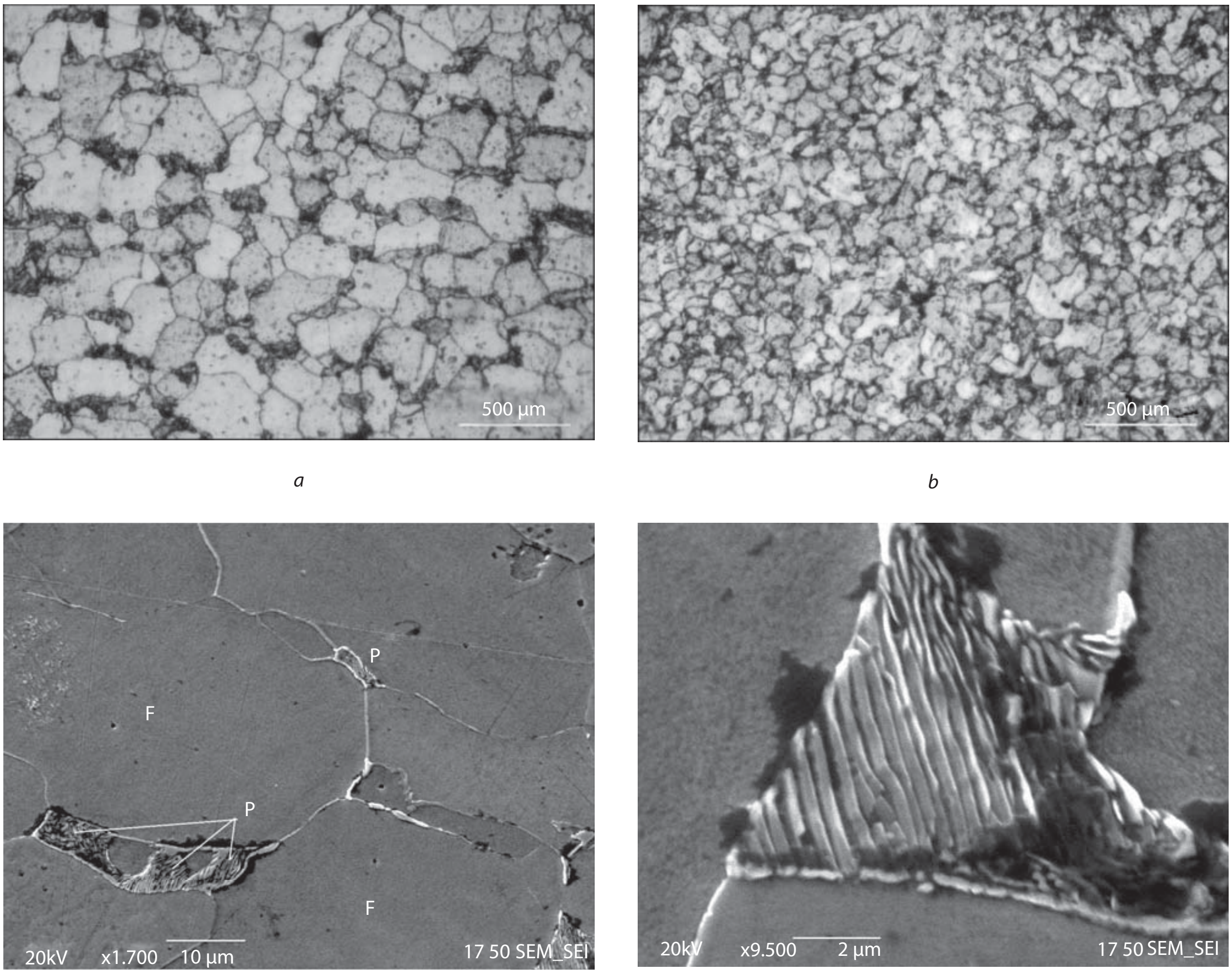
To obtain more reliable impact strength values within the range of T-B transition, not less than 5 samples were tested at each temperature. Location of the samples within the range of T-B transition was determined on the base of their surface destruction features. Not completely destructed samples (with their halves not separated after impact bending tests) were separated via additional break for investigation of Fractographic features. Macrofractographic analysis was conducted using the macro-shooting system. The mask was applied on the tough and brittle fracture components (see Fig. 1). When determining the relation between the brittle and tough fracture components, additional break and splitting areas were excluded. Determination of the parts of the brittle and tough fracture components was conducted via comparison of actual squares of macroscopic fracture projection.

Obtained results

Mechanical properties for wall extension of C-Mn-Si composition, which was formed via WAAM process, are presented in the work [12]. Microstructure of built-up welded samples for impact testing is displayed on the **Fig. 2**. It is seen that fine-grained ferrite structure of wall C-Mn-Si composition formed via WAAM process is the same as in direction of built-up welding (see Fig. 2, *a*), as well as in vertical direction of samples cutting (see Fig. 2, *b*). It can be identified as polygonal equiaxial isomorphic ferrite, a kind of primary ferrite; it is formed at low cooling rates, when diffusion transformation occurs at high temperatures both inside former austenite areas and near the boundaries of grains and crystallines. The grains of polygonal ferrite have approximately equiaxial (polyhedral) shape with equal grain boundaries (see Fig. 2, *c*). Mixture of microstructures of needle ferrite, allotrimorphic ferrite and bainite is observed in the upper part of built-up welded wall because this part was not subjected to thermal effect of consequent built-up rolls. The rest part of wall is characterized by uniform microstructure of polygonal ferrite with pearlite additive (see Fig. 2, *c* and *d*). As soon as only one roll is applied in each layer, heat input is equally distributed in all layers and, respectively, such microstructural homogeneity is observed.

Built-up welding in the first experimental series was carried out in the gas mixture. The quantitative parameters of impact strength within the range of T-B transition are presented in the **Table 1.**

Each series of samples includes 5 pieces, the value of impact strength in each series was averaged, average hardness of samples during the tests is presented in the table additionally. The range of variation between the minima and maximal values of impact strength for each experimental series can be evaluated and presented as additional information. Despite essential dispersion of impact strength values of the samples,



a *b*

c *d*

Fig. 2. Microstructure of built-up welded samples for testing on impact strength:
a – microstructure in direction of built-up welding movement; *b* – microstructure in vertical direction; *c* – microstructure in direction of built-up welding movement (F – ferrite, P – pearlite); *d* – pearlite colony along the ferrite grain boundaries; optical microscope (*a*, *b*), electronic microscope (*c*, *d*)

Table 1. **The results of impact bending testing at different temperatures**

No. of series and samples	Direction	Temperature, °C	Impact strength KCU, J/cm²	Range of variations KCU, J/cm²	Hardness, HB
1	Horizontal	+20	275	22.4	158
2		0	215	31.5	161
3		-20	178	35.8	157
4		-40	77	41.7	156
5		-60	38	49.8	159
1	Vertical	+20	292	17.5	162
2		0	253	21.7	159
3		-20	198	33.8	153
4		-40	82	37.9	164
5		-60	41	41.1	158

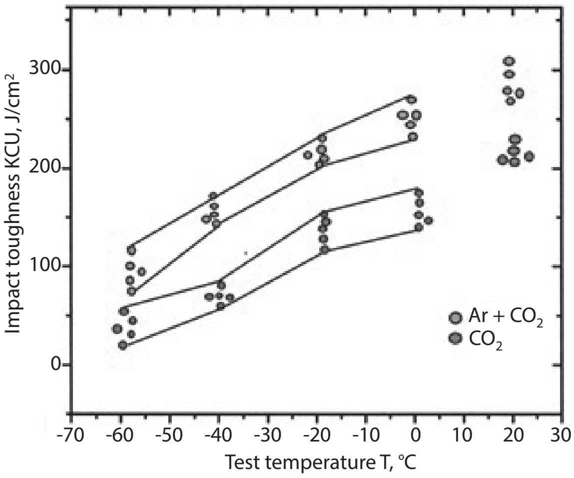


Fig. 3. Temperature relationship of impact strength KCU after additive built-up welding in different gases

it should be noted that the samples which were fabricated along direction of built-up welding are characterized by lower impact strength than the samples which were cut along vertical plane. If we consider the results depending on the testing temperatures, we can see influence of direction of samples cutting during impact strength testing. The samples which were cut along vertical plane are characterized by higher impact strength values in comparison with the samples which were cut along direction of built-up welding.

The results of testing of the samples with U-shaped notch for different gas mixtures are shown on the **Fig. 3**. The upper part of the T-B transition (upper threshold of cold brittleness) is located in the area 0 °C. All samples destructed at the temperatures from -60 °C to 0 °C displayed mixed type of destruction. Completely tough destruction was observed at the temperature +20 °C. The kinds of fractures of the samples, which were tested for impact bending and which are related to the groups with high and low impact strength, are different. The samples with high impact strength are characterized by forming the cleavage facets after propagation of a tough crack to the middle of the sample; it accompanies by substantial widening opposite to the notch and narrowing under the notch (see **Fig. 4**, *a*). Tough fracture with a mask is displayed from the top, and without a mask – from the bottom. Forming of brittle fracture directly under the notch without any significant plastic deformation of the sample is typical for the samples related to the group with low impact strength (see Fig. 4, *b*).

The data on evaluation of tough and brittle components in fractures of the samples after impact testing at different temperatures are presented in the **Table 2**. Comparison by the type of used gas is a feature of the obtained data. It can be seen that more than 50 % of the tough component in fracture is saved in the gas mixture (Ar+CO_2) to the temperatures (- 40 °C), while during built-up welding in the atmosphere of free carbon dioxide gas the tough component is equal to 40 % just at (- 20 °C), and at (- 40 °C) it lowers to 13 % (**Fig. 5**).

Discussion of the results

The results of earlier conducted researches displayed that the metal of C-Mn-Si composition, which was formed via the new WAAM process, is characterized by the complex of high mechanical properties in comparison with the metal obtained via conventional metallurgical technology [12]. In this work the authors added those results by important data about examination of impact strength at different temperatures. It was established during these studies that the samples cut in vertical direction manifest higher impact strength values that the samples which were cut in direction of built-up welding. It shows that essential anisotropy takes place in built-up welded walls. The results of testing of all samples display high variation of impact strength values, but it should be noted that the tendency of low values of impact strength for the samples which were cut in direction of built-up welding is observed not depending on the testing temperature. Additionally, average impact strength of the samples cut in vertical direction is substantially higher during testing at the temperature within the range from +20 °C to -20 °C in comparison with the samples which were cut in direction of built-up welding. Obtained impact strength values for the samples which were cut both in direction of built-up welding and in vertical direction of wall

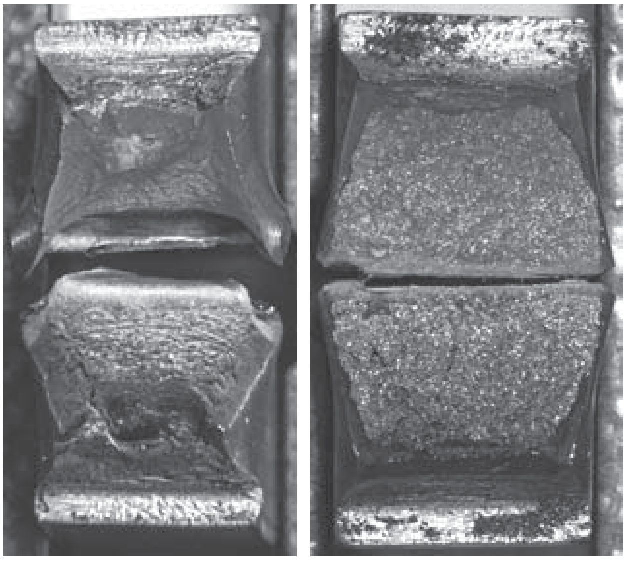


Fig. 4. Pictures of fractures of the impact samples with high (*a*) and low (*b*) values of impact strength

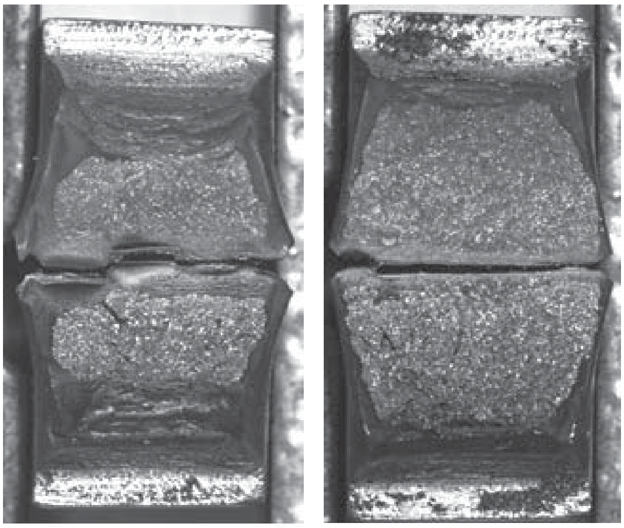


Fig. 5. Comparison of the tough component in fracture of the samples at (- 40 °C) for the gas mixture (Ar+CO_2) (*a*) and pure carbon dioxide gas (*b*)

Table 2. **Evaluation of the tough and brittle components in fractures at different temperatures**

Testing temperature, °C, and kind of gas mixture	Brittle destruction		Tough destruction	
	Number of pixels	%	Number of pixels	%
20, (Ar+CO_2)	0	0.00	26260	100.00
-20, (Ar+CO2)	26693	47.25	29803	52.75
-40, (Ar+CO_2)	23605	48.41	25155	51.59
20, CO_2	0	0.00	34429	100.00
-20, CO_2	29552	59.98	19717	40.02
-40, CO_2	47984	86.97	7187	13.03

plane are higher than the values of metal impact strength for rolled sheet made from 09G2SA steel.

It is known that low-alloy metal of C-Mn seam, which were produced using multi-pass welding, have average impact strength of seam metal ~160 J/cm² at (-20) °C [10,11]. Relation between microstructure and impact strength for metals of multi-pass seam is very complicated, because different factors can have positive and negative effect depending on studying material and its microstructural state [21-23]. In addition to microstructural components, influence of secondary heating, presence of micro-phases and inclusions [13-17] are recognized as critical factors, having the effect on microstructure and, respectively, on impact strength.

The authors have established that the kind of protective gas has influence on impact strength parameters (see the Fig. 3). Fractography of fractures for C-Mn-Si compositions, which were obtained via additive technology using carbon dioxide and mixture, displays a tough pit type of destruction [12]. Taking into account that Mesnager sample is more sensitive for brittleness due to weakening of grain boundaries, inclusion lines and segregation heterogeneity [22, 23], this work used KCU evaluation of built-up welded metal. Impact strength of the samples, which were obtained using gas mixture, is higher in comparison with impact strength of the samples in carbon dioxide. Impact strength of the samples made from standard 09G2SA steel is essentially lower than for metal of C-Mn-Si composition, which was obtained via additive technology [12]. As for C-Mn-Si composition, which was obtained using carbon dioxide gas, large pores were revealed in fracture cross section; it had influence on the results of testing for static extension and impact strength [12].

It should be noted that large part of brittle fracture appeared during impact bending testing of the samples which were built-up welded in carbon dioxide gas; it testifies about material location within the critical range of cold brittleness temperatures. The authors suggested that it was connected with large amount of pores in fracture cross section [12]. Attention should be paid to deviation of variations from minimal value to maximal one for different kinds of protective gas (see Fig. 3). It is especially seen at the temperatures (- 60 °C), 0 °C and + 20 °C. As for temperature (- 40° C), the compact type of impact strength values is seen for both gas types. The interval of T-B transition is characterized by increased dispersion of impact strength values in comparison with statistical one. Dual character of lowering the impact strength values was observed with decrease of the testing temperature. Such dual character is often described by upper and lower envelope curves. Decrease of the maximal impact strength values with lowering the testing temperature had monotonous and practically linear character.

The main feature of samples destruction within the T-B transition range is presence of micro-cracks, besides combined destruction character. Such micro-cracks can be observed both in the areas which has common boundaries with destruction surface (branches from the main micro-crack) and under destruction surface (residual micro-cracks). Analysis of these micro-cracks displayed [12] that those of them which were fixed under splitting are caused by brittle transcrystalline cleavage, while micro-cracks located under the surface of brittle fracture component are resulted by tough tearing-off. High degree of plastic deformation was observed in the plastic area of samples under splitting and under tough component. Microstructure heterogeneity can be a possible cause of forming the sources of plastic areas with various toughness.

Mechanical properties were determined not only by manufacturing method, but also by metal structure. It is known [22, 23] that excessive amount of polygonal ferrite leads to decrease of resistance to brittle destruction, because crack in coarse ferrite grains propagates easily in straight direction, until it varies this direction from grain boundary. Prediction of impact strength on the base of microstructural parameters of welding seam metal is difficult due to large number of influencing parameters [20-23].

Multiple literature data of national and foreign researchers testify that needle ferrite structure is considered as the most favourable from the point of view of high cold resistance provision for low-alloy seam metal. Usual practice, which connects this property with microstructure of multi-pass welding roll, was considered as unsatisfactory, because the amount of needle ferrite as the most favourable component not always can be the main factor having the effect on impact strength. Needle ferrite has essential influence on impact strength of welding seam metal due to its fine grain sizes and mutual connected structure with high angular boundaries, which act as an obstacle for crack propagation and in such way improve impact strength [15-20]. Additionally, needle ferrite is the most favourable microstructure component. Though impact strength of seam metal was for many decades connected with amount of needle ferrite in the upper roll of welding seam, it is known that microstructure responding for mechanical properties is not met in the last welding pass. It is stipulated by recrystallization effect with decisive influence on mechanical properties, which is caused in the most application areas by additive technology of layers applying similar to multi-pass welding.

Positive effect of multi-pass welding on seam metal properties was noted by many researchers. This effect was manifested via volume decrease and refining of coarse crystalline cast structure of seam metal, as well as owing to forming the areas with fine-dispersed structure, which appear due to “annealing” effect of conducted built-up welding passes over previous rolls. Applying to the features of additive built-up welding, relationship between cast coarse-crystalline and recrystallized structure in the metal of built-up welded metal will play an important role for mutual relation of metal structure and cold resistance. Coarse-grained and fine-grained secondary heated areas demonstrate grain structure and microstructure with substantial variations in comparison with built-up welded metal (columnar area).

It should be mentioned in conclusion, that not many examinations were passed to research microstructural parameters of welded seam metal in multi-pass welding; it was caused by the above-mentioned complication. It is evident that knowledge about microstructure parameters in additive production has decisive effect for prediction of impact strength. Thereby more systematic research is principally important for reveal of this mutual connection between microstructure of the layers obtained via additive technology and strength parameters.

Conclusions

1. It was established that the values of impact strength in C-Mn-Si composition, which was formed via the new WAAM process, exceed the typical value for deformed 09G2S metal. Anisotropy of impact strength values exists depending on direction of samples cutting-off and kind of WAAM protective atmosphere, connected with use of different compositions of protective gases.

2. It is shown that relationship of cast and recrystallized structure has direct influence on metal cold resistance. When overrecrystallized structure is forming in metal seam cross-section in the amount 45-65 %, high values of impact strength in C-Mn-Si composition are provided in comparison with metal which was obtained via conventional metallurgical technology.

3. To provide high cold resistance of metal for the components of machines and mechanisms, which was obtained via the new WAAM process from C-Mn-Si composition, it is necessary to take into account during development of the technology the requirements of provision of optimal structural states via adjusting thermal cycle of forming. Use of the main metal with fine-grained structure and application of the efficient procedures of consequent heat treatment should be considered as well.

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