Magnetically impelled arc butt welding of high-strength steel tubular parts of hydraulic cylinder

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1. Introduction

In several industries sectors, a large amount of works is being done on welding hollow joint of pipe and tubular parts of hydraulic cylinders with Ø = 30 mm to Ø = 220 mm with wall thickness (WT) δ = 4 mm to δ = 10 mm operating under high pressure. In this scenario, arc welding processes are the main technology used.

The development of technology and equipment for press-type welding in stationary conditions would significantly increase the labor productivity in industry and improve the stability of the joints quality [1-4]. The experience gained by the E.O. Paton Electric Welding Institute NAS of Ukraine (PWI) over the past decades in the field of pressure welding of pipes has shown the promise of such developments on the basis of the method of magnetically impelled arc butt welding (MIAB), being successfully implemented in the manufacturing of several tubular assemblies at automotive plants, pipeline welding in the construction of complex greenhouse complexes and in pipeline welding at temperaturecondition +40 °C to -40 °C [4-6].

The purpose of recent studies carried outat the PWI was the development of a technology leading to improved production rate and cost reduction through application equipment for MIAB welding hydraulic pipes with a bottom (Figure 1) of different assortment and chemical composition of steel with diameters up to Ø = 200 mm with wall thickness of up to δ = 10 mm, covering the most demanded assortment of tubular parts for the manufacturing of hydraulic cylinders with working pressure to 250 bar.

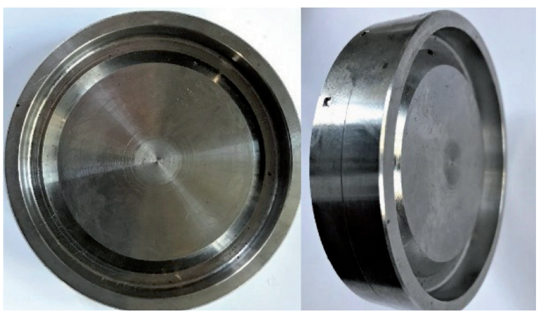

Figure 1. Design of bottom of hydraulic cylinder.

Hydraulic cylinders are widely used in all branches of industries where a positive displacement hydraulic drive is used. For example, in road-building, earthmoving, hoisting-and-transport vehicles, in aviation, as well as in technological equipment - metal-cutting machines, forging and pressing machines.

2. Materials and Experimental Procedure

Aiming the real case analyze of the process developed, the welding procedures were performed on base metals co mmonly used on hydraulic cylinders. The chemical composition of the studied pipe steels is given in Table 1.

Table 1. The chemical composition of steels, [%].

Steel Grade	DIN 17100 St52-3	ASTM A615 Grade 520	JIS STKM13C
C	0.18	0.159	0.25
Si	0.52	0.172	0.35
Mn	1.35	1.19	0.49
P	0.02	0.012	0.035
S	0.03	0.006	0.034
Cu	0.28	0.13	0.08
Ni	0.24	0.04	0.03
Cr	0.23	0.04	0.03
Mo	-	0.03	0.01
Ti	-	0.002	-
Nb	-	0.002	-
B	-	0.001	-
Al	-	0.03	-

All welded joining processes were tested in accordance with the international API standard [7], and additional bend tests were performed in accordance with departmental procedures and standards, in order to prove their quality for real applications.

Metallographic examinations were performed after etching in 4% solution HNO_3 in alcohol. The microhardness measurements were carried out on LECO M-400 hardness tester. Taking picture of the structure of the welded joints was performed on the Neophot-32 optical microscope.

2.1. Rotation Arc Control

The MIAB process is characterized by the fact that the arc under the influence of the external control magnetic field, moves in the gap between the ends of the tubular parts to be welded. The relatively high speed of the arc movement, up to 210 m/s, allows the redistributing thermal energy of the welding arc over the entire surface of the ends of the hollow parts. A relatively uniform heating of the butts of pipes to be welded is achieved. A welded joint is formed during upset and joint plastic deformation of the butts of parts [8]. The process of welding parts of hydraulic cylinders is performed in air, without the use of shielding gases.

Taking into account different conditions of heat removal from the parts, the purpose of the investigations was to find the ways for control the heating process, providing a steady movement of the welding arc across the entire cross-section area of the butts of pipe and bottom, achieving a relatively uniform heating.

As a result of the investigations carried out at the PWI, a method was developed, whichto control the movement of the arc across the entire cross-section of the pipes. The process of heating the ends is carried out by moving the welding arc on the outer edges, in the area with a higher value of a radial component of the control magnetic field (CMF) induction magnetic field (Figure 2).

Figure 2. Traces left by welding arc during heating of the outer edge pipes.

After achieving a uniform heating, the temperature at a distance of 2 mm from the end of the pipe reaches a value between 970 °C and 1020 °C, which provides the necessary conditions for plastic deformation of the joint, a program change in the technological parameters of welding, which leads to a short-term t = 0.4 s increase of the welding currentwhich leads to increase temperature at a distance of 2 mm from the ends to be welded to a value between 1250 °C and 1300 °C the moment before upset and simultaneous radial movement of the welding arc by the interaction of radial component of arc current with the axial component of the induction magnetic field on the surface of the pipe and bottom butt, for example as hollow parts Ø = 90 mm, δ = 5 mm (Figure 3). The quality formation of the welded joints of the pipe with bottom can be provided without any gas shielding under the condition that the frequency of the arc rotation at the moment before upset is selected so that the layer of melt metal at any point on the surface of the ends does not have a time to solidifyat the time intervals when the arc passes through these regions. Then upset is performed.

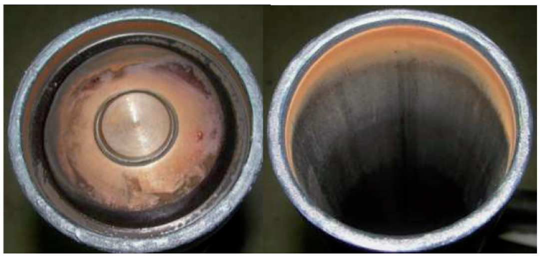

Figure 3. Surfaces of buts pipe and bottom are covered with a layer of melt metal before upset.

On the basis of these investigations the system of automatic control of the process of MIAB welding pipe with a bottom, the optimal programs for changing the basic parameters in the process of welding, andalso the algorithms for their controlwith the use feedbacks were developed [5].

High-strength high-pressure steel tubular parts are used in the manufacturing of hydraulic cylinders. A picture of the appearance of welded joint Ø = 125 mm and δ = 7.5 mm, welding time 37 s, with outside height of crown flash up to 1.8 mm is shown in Figure 4.

Figure 4. Welded joint pipe with bottom.

For comparison, when applied of conventional process such as MIG/MAG welding with joint preparation for Ø = 125 mm and δ = 7.5 mm, welding time 112 s, three times the need in MIAB welding process.

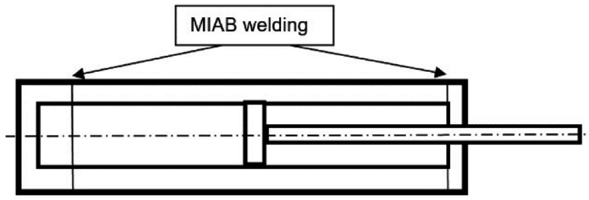

Figure 5. Application MIAB for welding hydraulic cylinder.

MIAB welding with uniform heating around cylinder circle can be carried out in a vertical and horizontal position. Also, MIAB can be applied for final weld assembly hydraulic cylinder, Figure 5.

3. Results

In accordance with the API 1104 standard [7], mechanical testing, such as tensile, bending, microhardness measurement and metallographic examinations were performed for all the welding tests performed. In the Figure 6 is illustrated the results of the bending testing of the welded joints.

Figure 6. Results of bending tests of welded joint.

Also was carried out hydraulic pressure tests result of welded joint up to 690 bar (Figure7), for welded joint pipes Ø = 58 mm and δ = 4 mm type STKM13C.

Figure 7. Hydraulic pressure tests result of weld joint.

Mechanical tests were carried out on 3 welded sizes of hydraulic cylinder parts each diameter at Table 3. For other sizes was carried out hydraulic tests at customer requirements.

Table 3. Mechanical properties of welded joints.

Steel Grade	OD/WT [mm]	σ_t [MPa]		KCV_{20} [J/cm^2]	
		Base Metal	Welded Joint	Base Metal	Welded Joint
JIS STKM13C	88.5/4.75	522 ± 17	517 ± 16	-	-
DIN 17100 St52-3	90/5	503 ± 15	486 ± 8	-	-
ASTM A516 Grade 520	121/7	697 ± 16	638 ± 11	145 ± 28	127 ± 59
ASTM A615 Grade 520	121/10	652 ± 19	646 ± 40	135 ± 27	122 ± 42
JIS STKM 13C	186.6/7.8	541 ± 10	524 ± 5	-	-
DIN 17100 St52-3	188/8.5	502 ± 15	484 ± 8	-	-

Technologies of MIAB welding parts of hydraulic cylinders and welding equipment were developed. The main parameters characterizing welding modes are given in Table 4.

Table 4. Main technological parameters of welding

Type of Steel	OD / WT	Welding Time [s]	Upset [kN]	Shortening parts [mm]
DIN 17100 St52-3	42 / 5	11	42	3.9
ASTM A615 Grade 520	60 / 5	17	55	4.7
DIN 17100 St52-3	73 / 5	21	62	4.8
JIS STKM13C	88.5 / 4.75	25	91	4.7
DIN 17100 St52-3	90 / 5	24	97	4.7
DIN 17100 St52-3	125 / 7.5	37	257	7.2
ASTM A615 Grade 520	121 / 7	35	250	6.9
ASTM A615 Grade 520	121 / 10	43	278	9.1
JIS STKM13C	186.6 / 7.8	51	290	7.1
DIN 17100 St52-3	188 / 8.5	75	320	7.7

Comprehensive mechanical tests showa practical equal strength of welded joints and base metal and meet the standard requirements.

3.1. Metallurgical Analysis

Metallographic examinations were performed on the melted buttfrom steel DIN 17100 St52-3 OD90x5 mm (Figure 2) at the moment before upset and in the weldedjoint OD125x7.5 mm (Figure 3).

The specimens for investigations were manufactured on highspeed discs using diamond pastes of different dispersion. Revealing the structure was performed by chemical etching in a 4% HNO_3 in ethyl alcohol. Examinations were performedin Neophot-32 and Poluvar at different magnifications. The hardness of the melt layer was measured on the LECO M-400 hardness tester.

Specimen after heating without upset (Figure 2). At the fused end of the specimen there is anarea with a cast structure (Figure8). The width of the area is 300 - 400 µm. The structure of metal is ferrite-pearlite, ferrite is released along the crystallite boundaries. At this area, polygonal and Widmanstätten types of ferrites were found and along the crystallite boundaries polyhedral one (in a small amount) was detected. The hardness in this area of HV_1 1850 MPa - 2240 MPa. At the overheating area, the structure consists of upper and lower bainites with a hardness of HV_1 2830 MPa - 3480 MPa. The width of this area is 2000 µm, then inthe structure perlite appears, the amount of bainite is reduced, the hardness decreases to HV_1 2490 MPa; HV_1 2450 MPa.

At the area of complete recrystallization, the structure is small, consisting of ferrite, perlite, and a small amount of bainite. In the structure, the traces with bands appear (Figure 9), which are absent in the overheating area (Figure 10). The hardness is HV_1 2060 MPa - 2240 MPa.

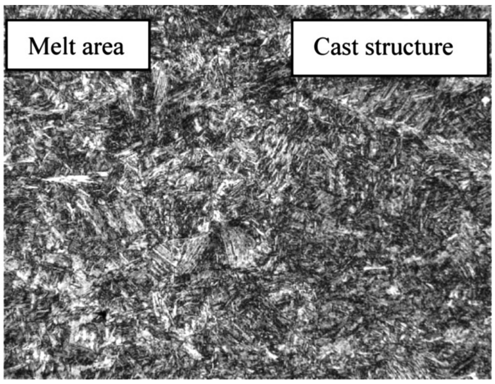

Figure 8. Microstructure (x200) of cast metal and melt area.

The area of incomplete recrystallization after upset has a fine-grainedferrite-pearlite structure (grain number 9) where the bands of ferrite and perlite alternated (Figure 9). The hardness of the metal at the area HV_1 1880 MPa to HV_1 1960 MPa (ferrite) and HV_1 2060 MPa -2240 MPa (perlite).

The base metal has a ferrite-pearlite structure in the form of bands with a ferrite grain score of Nos 7-8 and a hardness HV_1 1870 MPa -1760 MPa.The width of the heat affected zone (HAZ) is 4000 µm.

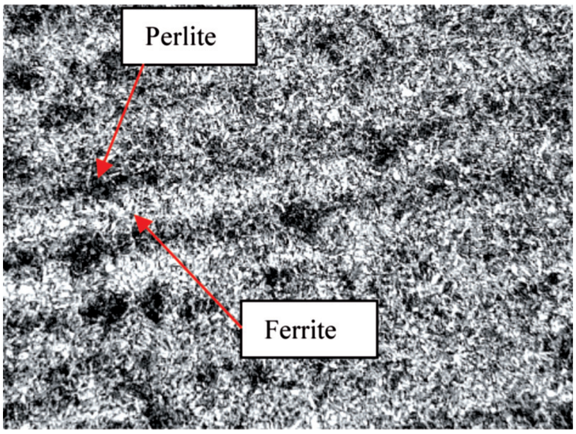

Figure 9. Microstructure (x200) of the area of complete and incomplete recrystallization on the bottom side.

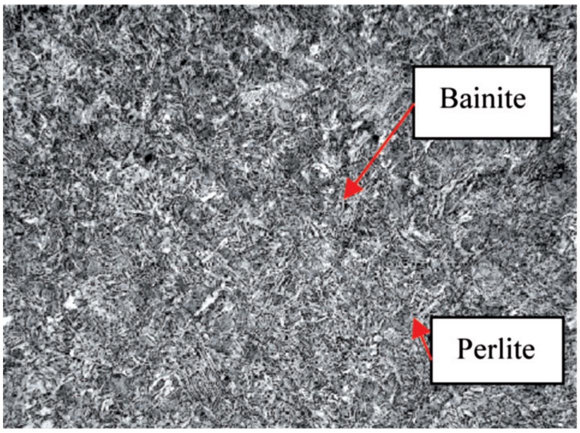

Figure 10. Microstructure (x200) of the overheating area on the bottom side.

Macro section of the welded joint pipe and the bottom OD 125x7.5 mm is shown in (Figure11). The joint line represents a discontinuous white band of up to 40 μmthickness in the central zone of the welded joint and extends up to 80 μm to the edges of the specimen. The structure of the joint line is ferrite with the hardness of HV_1 1650 MPa -1810 MPa. From the distribution of hardness, it is seen that the joint has a slight increase in the hardness of the ferrite band to HV_1 1800 MPa, which is higher than the hardness of the base metal of tubular parts. The distribution of hardness at the joint indicates the absence of significant changes in strength at the main areas of the weld. The values of hardness on the joint line are also close to the similar values of the base metal. During MIAB welding the structure of metal in the HAZ is more homogeneous. No defects on the joint line pipe and the bottom OD 125x7.5 mm were detected (Figure12).

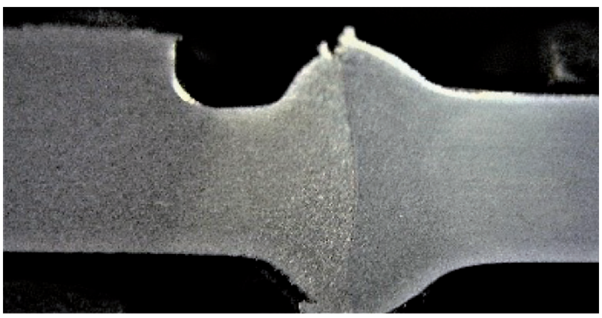

Figure 11. Macro section of the welded joint.

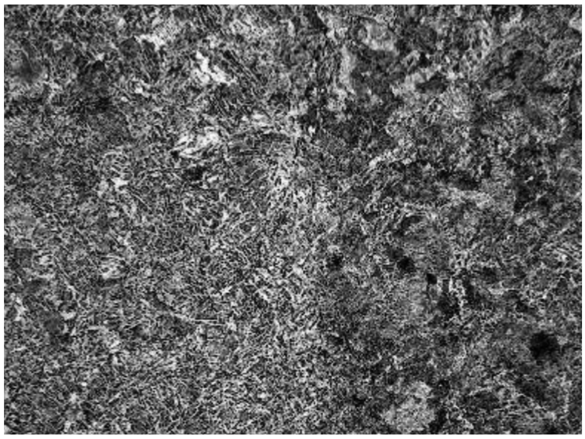

Figure 12. Microstructure (x200) of welded joint.

The structure of the overheating area on the side of the bottomhas small regions of perlite and ferrite of different modifications, mainly ferrite with an ordered second phase. In addition, there is polyhedral ferrite, Widmannstätten ferrite, polygonal ferrite in the form of fragments of ferrite bands along the borders of former austenitic grains.

The hardness of the metal in this area is HV_1 1830 MPa - 2160 MPa (Figure 13).

With distance from the joint line, the structure is refined, the number of polygonal and polyhedral ferrite increases.

At the area of complete recrystallization, the structure is fine-grained (grain number 10–11) ferrite-perlite.

Figure 13. Microstructure (x200) of the overheating area on the bottom side.

The base metal has a pearlite ferrite structure (grain number 8)and the hardness of HV_1 1560 MPa - 1760 MPa. The HAZ width is approximately 6000 μm.

The overheating area on the pipe side (Figure 14) has almost the same structure as the area on the side of the lid. The difference is that the predominant amount of ferrite with a disordered second phase and structure on the overheating area are finer. The hardness of the metal in the overheating area is HV_1 1780 MPa - 2060 MPa. With distance from the joint line, the structure is refined. The width of the overheating area is 2700 μm. The width of the overheating area is smaller after upset and is 2700 μm as compared to 3500 μm after heating without upset.

The structure of the area of complete recrystallization of ferrite is pearlite fine-grained with predominance of the ferrite component (Figure 15). Traces of the bands are visible at the area of incomplete recrystallization. The bands appear in the area of partial recrystallization. The structure in this area is ferrite-pearlite, consisting of alternating bands of ferrite and perlite.

The heat-affected zone (HAZ) width is approximately 5000 μm.

The base metal represents a fine-grained (grain number 10-11) ferrite-perlite structure (Figure 16) with a hardness of HV_1 1660 MPa - 1990 MPa.

Figure 14. Microstructure (x200) of the overheating area on the pipe side.

No defects are observed in the HAZ. The hardness of the pearlite strip HV_1 is 2050, 1990, 2050 MPa. The hardness is nearby in the pearlite-ferrite mixture HV_1 1560 MPa - 1600 MPa.

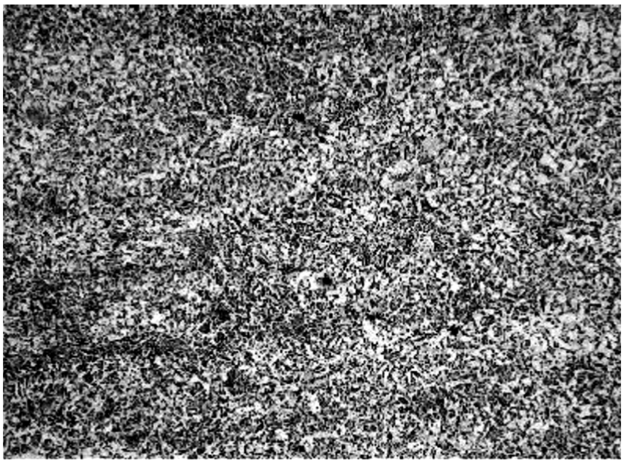

Figure 15. Microstructure (x200) of the area of complete and incomplete recrystallization on the pipe side

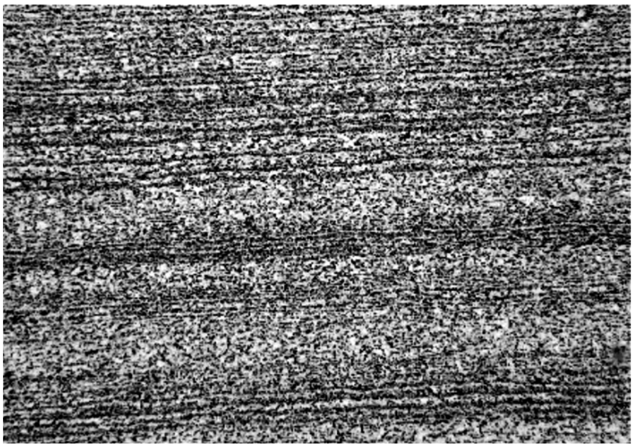

Figure 16. Microstructure (x200) of base metal of the pipe

3.2. MIAB Welding Systems for Hydraulic Cylinder

For MIAB welding tubular parts of hydraulic cylinders, the MD-205 machine was designed, which provides an industrial welding in stationary conditions (Table 5). Using this technology, more than 27,000 parts of hydraulic cylinders with OD 42 to OD 178 mm were welded (Figure 17).

Table 5.Technical Specifications of the machine forwelding ofhydraulic cylinders.

Type Machine	MD-205
OD Pipe (mm)	30 – 200
WT Pipe (mm)	3 – 10
Efficiency (joints / h)	80
Power Consumption (kVA)	120
Weight (kg)	1500

Figure 17. Hydraulic cylinders ready for operation

The MD-205 machine (Figure 18) is designed for MIAB welding of tubular parts for various purposes and consists of welding head, hydraulic pump station, control cabinet with a portable control panel, DC power supply of welding arc.

Figure 18. Welding machine MD-205

The welding machine MD-205 is a tong-type, which is characterized bya separate clamping of the pipes to be welded.

In terms of design, the machine is capable of loadingand unloading welded pipes to the side. MIAB welding machines and technology provide the required axial accuracy of the welded joints of hydraulic cylinders. Precision upset allows you to get the specified length of the cylinder body part.

4. Conclusion

The objective of this work was to evaluate and develop the magnetically impelled arc butt welding technology applied in high-strength steel tubular parts of hydraulic cylinder.

From the results obtained, it was possible to conclude that:

• The optimal condition's distribution of the induction control magnetic field was determined which allow a steady movement of the welding arc in a narrow gap to achieve relatively uniform heating of welded butts of the hydraulic pipes with different wall thickness from 3 mm to 10 mm.

• A control method has been developed that allows moving the arc over the entire welding cross-sectional area of pipes exceeding the sizes of the active spots of the arc column and forming a uniformly distributed melt on it and to achieve a quality weld joint.

• The main technological parameters of MIAB welding for the precision forming welded joint of tubular parts different OD 40 mm to OD 200 mm and WT 3 mm to WT 10 mm of hydraulic cylinders were determined.

• Technologies of MIAB welding of high-strength steels were developed to improved production rate and cost reduction covering the most demanded assortment of tubular parts for the manufacture of hydraulic cylinders with working pressure to 250 Bar.

• The developed MIAB equipment proved to be extremely repetitive and reliable, with satisfactory results even after 27,000 parts of hydraulic cylinders were welded.

These results corroborate theimportance of studying and developing MIAB processes and equipment for application in the industry.

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