ADVANCED ARGON-ARC WELDING PROCESSES OF AIRCRAFT STRUCTURES FROM HIGH STRENGTH STEELS AND LIGHT ALLOYS

Prof. M. Chtrikman
National Research Institute of Aviation Technology (NIAT)
13'a, Gzelscy, Moscow, 107120, Russia
Tel./Fax: (095) 278-63-81
aef@rambler.ru

Abstract

Requirements to fabrication processes for arc welding of highly loaded thick-walled joint and problems of research and development in terms of the tendency for the modern aircraft structure development are outlined. A justified, choice of the development line of the new promising welding processes for solution of these problems is presented. A complex of new welding processes and technologies for making highly reliable joints with different thickness (u to 120 mm and more) and length of weld (up to 0.1 m; 0.1-0.5 m and more than 0.5 m) has bee developed. It is shown that the possibility to control the heat flow distribution over the groove surface of the welded joints provides for improved reliability. The new welding processes are equipment are effectively used in serial production of the Mykoyan and Sukhoi supersonic aircrafts as well as in AN-124 Ruslan and AN-225 Mriya wide body aircrafts.

Keywords: thick-walled joints, narrow gap welding, heat distribution, holes, vertical welding.

1. Introduction

The tendency for an increase in the limit loads on the supersonic aircraft structures and economic considerations stipulated the change-over to the all-welded assemblies. A wide variety of geometric shapes of welded structures, including highly loaded joints components with a wide range of the weld length (0.06-8 m) and welded thickness (up to 100 mm and more) is observed. Load - carrying joints subjected, as a rule, to tensile and bending dynamical and other loads should possess rather high characteristics of plasticity and toughness of the weld and areas around the weld as well as resistance to crack propagation along with high strength and low-cycle fatigue characteristics. Substitution of welded joints for other types of joints (riveted, bolted, etc.) allowed for elimination of the geometrical stress concentrator and sharply increasing thereby the uniformity (smoothness of transmission) of the force flow. However under the influence of the welding thermal cycle a considerable phase and structural inhomogenuity is developed, especially while welding hardenable by heat treatment high-strength alloys and steels [I]. With an increase in thickness of the components being welded, inhomogenuity of the metal in the joints grows.

Based on the aforementioned the following problems should be solved in the present paper:

-development of the automated processes for argon-arc welding of the load-carrying joints of the thick-walled (10-100 mm and more) structural elements with large (>0.5 m), medium (0.1-0.5 m) and small (< 0.1 m) length of the weld;

-determination of the following relation: fabrication parameters - structure and formation of the weld - joint properties to use it in an automatic welding process control system;

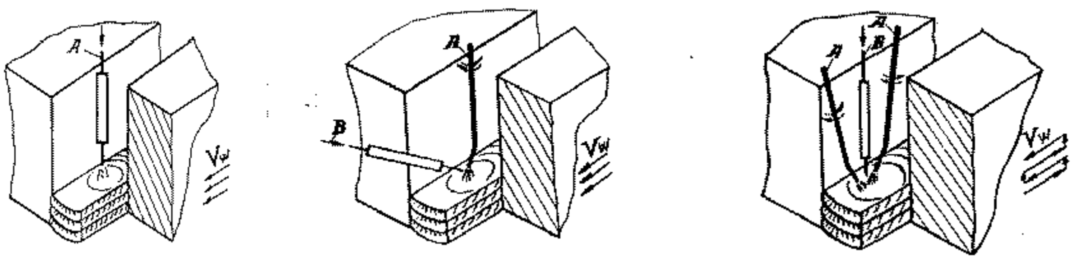
- development of new welding technologies and equipment providing for the possibility of their application under conditions of general assembly (during mounting), reduction of the scope and labour content of the non-destructive testing of the joint quality.

The research has shown that for solution of the most above set problems it is necessary to develop welding processes using narrow gap groove of the welded thick-walled components.

2. Narrow gap welding process

The process of consumable electrode inert gas narrow gap welding is best investigated and used for thick-walled joints of large (more than 5 m) length in shipbuilding, power engineering and other industries. In co-operation with the Tupolev Aircraft Research and Engineering Complex we have developed and successfully used in production of their aircraft consumable electrode narrow gap welding process according to the diagram presented in Fig. la. A special welding head with an overheating protection is placed into the narrow gap groove; gas shielding devices provide for reliable protection of the welding area. However the consumable electrode narrow gap welding process in spite of its high efficiency may be considered promising only for not highly loaded joints of large length.

For welding highly loaded joints having weld length less than 0.5 m with more stringent requirements being placed upon the quality and stability of their formation, no adequate technology was available. The simple substitution of the nonconsumable electrode for the consumable one both during manual and automatic argon-arc narrow gap welding did not ensure the consistent formation of the weld with reliable fusion along its boundary due to the impossibility to control the heat flow distribution along the groove surface.



a) b) c)

Fig 1. Process diagram of the narrow gap welding with consumable electrode (a) and one (b) or two (c) scanning nonconsumable electrodes. A - electrode, B - filling wire, V_w - welding direction

The problem of making joints with higher reliability was solved by NIAT in co-operation with the plants, when a new process of the automated argon-arc scanning nonconsumable electrode narrow gap welding (with one or two electrodes) was developed according to diagram in Fig. 1b,c The process enables control of the heat flow distribution over the edges all round the narrow gap groove thanks to the application of a tungsten electrode (or two electrodes) with the offset of its tip (cathode). The tap during electrode pendular oscillations scans lateral edges at regular intervals with the specified angle between the electrode and the edge surface.

Determination of the thermal fields from the suggested analysis using source method [2] demonstrated that the pendular oscillation of the electrode made it possible not only to control heat flow distribution over the edges being welded but to reduce substantially the energy parameters of welding. Thus, if in conformity to the analysis we arbitrarily substitute the action of the averaged constantly operating source for the action of the reduced pulsating (with the transverse arc oscillation) heat source then temperature at point M on the groove edge during welding of one layer may be expressed by the following equation [3]

$$T_{\mathrm{Mav}} = \frac{q \cdot K}{4\pi\lambda R} \cdot e^{-\frac{V \cdot x}{2a} - \frac{v \cdot R}{2a}} \qquad (1)$$

where

$K = \frac{R}{2R_1} - \frac{R}{2R_2}$ - coefficient taking into account the intensity of the change in power of the heat source while it approaches the edge, and

R_1, R_2, - current minimum and maximum distance from the heat source to point M respectively.

Having made the analysis we find that for the fusion isothermal line to pass through point M at the depth of 0.5 mm from the edge surface (on VNS2-type steel) with the transverse arc oscillation, welding current J_w, = 280A is sufficient, whereas for welding without the transverse arc oscillation it will require current of 480A. However with such high welding current penetration in the axial groove area would exceed the necessary depth (0.5 mm) 5-6 times. In the heat analysis, as applied to the upper layers of the weld, we have introduced coefficient 2 into equation (1) which accounts for transition of the heat source from the infinite to the semi-infinite body. During evaluation of the initial temperature influence (in welding of the previous weld layer) it has been found out by analysis that the influence of the periodic component in its action is intensively decreased with time and already in 20 minutes might not be taken into consideration. Thus the conditions of the fusion isothermal line passing through the specified point M are determined by the sum of temperatures from action of the i-th heat source and the constantly operating sources preceding the i'-th source

$$T_M = T_i + \sum_{i=1}^{i \to 1} T(Z_i, t_i) \qquad (2)$$

Determination of dependence of the penetration depth h_p on parameters of the welding conditions in the groove axial area by the analytical method is unacceptable due to the presence of the weld pool of considerable depth (δ_i). For this groove area a regression equation $h_p = 1.2\,\delta_i^2 - 0.5\,\delta_i - 6.9$ has been obtained and the correlation (in the form of a nomogram) between the depth of the weld pool (measured using special procedure) and penetration depth with parameters of welding conditions [4] has been established experimentally by mathematical planning.

The established relations (analytical - for the edges and regressive - for the groove axial area) may serve as an algorithm for development of the automatic systems for controlling process parameters with consideration of the thermophysical properties of the welded material.

The transverse arc oscillations during narrow gap welding thanks to periodic influence of the arc upon the crystallizing metal improve and refine weld structure. Experimentally found the optimal frequency of the electrode pendular oscillation ($f_o \cong 1$ Hz) wherein the minimum size of the grain and the maximum resistance to crack propagation during impact bending are provided for (Fig. 2, 3).

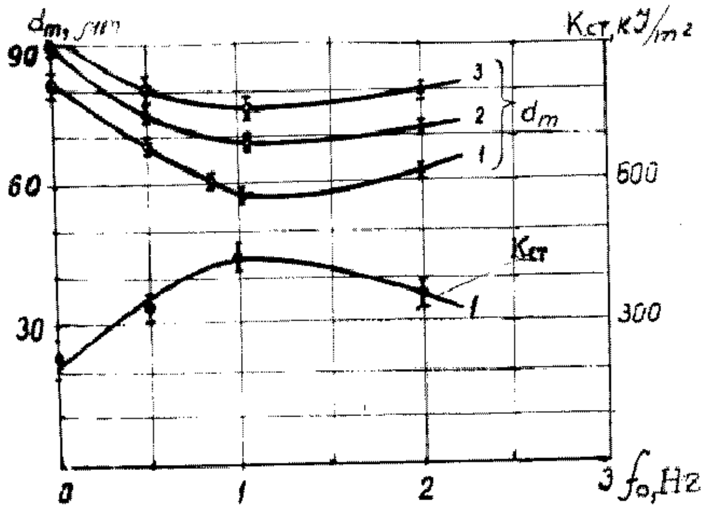
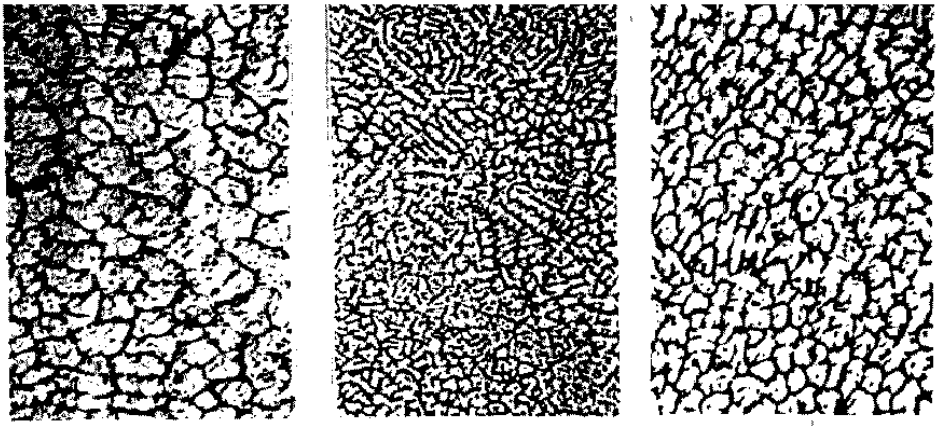


Fig. 2. Dependence of the grain size (dm) and resistance to crack propagation (K_{cr}) on the frequency of transverse arc oscillation (f_0). VNS2 steel. 1. 2 and 3: $q / V_w = 4 \times 10^2$; 1.0×10^3 and 3.5×10^3 kJ/m.



a) b) c)

Fig. 3. Microstructure of welds, $q/w = 1 \times 10^3$ kJ/m (x 300):
a) f_0 – 0 Hz; b) f_0 – 1.0 Hz; c) f_0 – 2.0 Hz;

A reliable protection from the atmosphere through the structural isolation of the welding area by the water-cooled microchamber with the flowing inert gas allows of obtaining pure, non-defective welded joints comparing well in terms of mechanical properties with electron-beam welding joints (Table 1).

Table 1 The mechanical properties of joints, made by different welding processes

CHARACTERISTICS	MATERIAL	WELDING TYPE		
		TiG (manual)	TiGngnc	Electron-Beam
Ultimate strength, *a, MPa.*	Steel	1060	1170	1200
	Titanium	720	800	820
Impact Toughness, KCU kJ/m^2	Steel	1370	2060	1760
	Titanium	480	765	820
Low-Cycle Fatigue $\sigma = 590$ MPa; N x 10^3 cycles	Steel	10	80	95
	Titanium	8	76	82

Note: Steel - VNS2. Titanium - VT6ch.

TiGngnc - automatic argon-arc scanning nonconsumable electrode narrow gap welding

The high and consistent quality of the joints and number of other advantages of the scanning nonconsumable electrode narrow gap welding made possible its application for serial production for fabrication of highly loaded joints of the wing pivot and the fuselage structural components for the Mykoyan and Tupolev Design Bureaux' aircrafts as well as landing gear cylinder girth joints for the wide-body AN-124 Ruslan and AN-225 Mriya aircrafts designed at the Antonov Design Bureau having the largest load-carrying capacity in the world -150 tonnes and 250 tonnes respectively.

3. Vertical welding with rotating nonconsumable electrode (VWRNE).

The most complicated problem - automation of the argon-arc welding of the short (<0.1 m) thick-walled joints of the load-carrying components of an aircraft structure, especially during assembly - was solved only with the introduction of a new welding procedure - vertical rotating nonconsumable electrode welding [5]. The flow-chart of the vertical rotating nonconsumable electrode welding (Fig. 4) consists in the following. A rotating electrode holder, the filling wire being fed along its axis, is placed in a deep (up to 120 mm) cavity formed by the edges of the welded components and special equipment or by drilling 12-20 mm diameter. While the electrode holder is lifted the arc burning from the eccentrically placed cathode is scanning the surface of the cavity on a spiral path providing for a reliable fusion of the weld with the cavity walls. This and compliance with certain values of the process energy parameters provide for consistent specified position of the fusion isothermal lines, i.e. for the necessary weld shape.

Vertical rotating nonconsumable electrode welding may operate in the automatic control system. For this purpose we determined the analytical dependencies of the heating temperatures on welding parameters and thermophysical properties of the materials being welded using analysis based on a conventional replacement of the actual heat source by a disc heat source with intensity $q_r = q/\pi r^2$ and employment of the fundamental thermal conductivity equation for an instantaneous disc heat source [2]. The solution of Vf = F(Jw, D) may be used for the automatic control system.

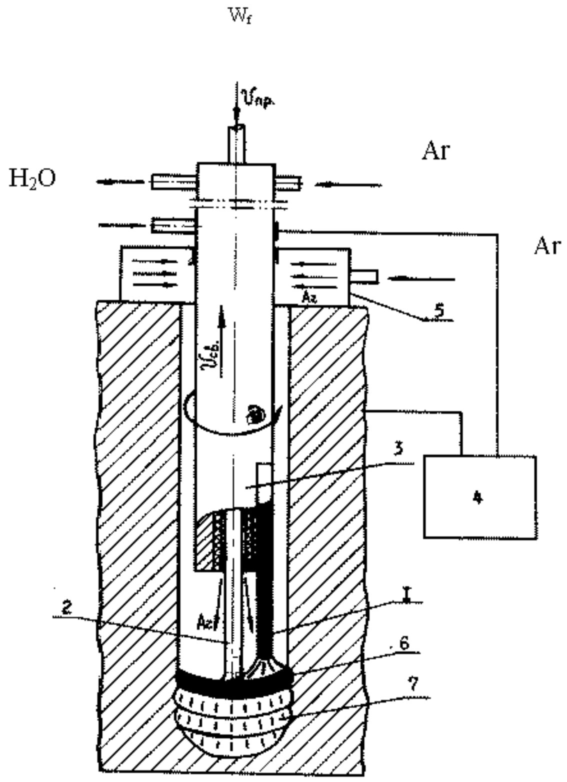


Fig 4. The scheme of vertical rotating nonconsumable electrode welding

1. – filling wire;
2. – electrode;
3. – electrode holder;
4. – arc – welding source;
5. – gas shielding device;
6. – pool;
7. weld.

Automation of welding short (<0.1 m) thick-walled (up to 120 mm) butt joints demanded different variants of preparation and butting of the components being welded according to the butt length. With the butt length L > 12...15 mm it is in the form of a hole and with the butt length up to 12...15 mm - with narrow gap groove (Fig. 5).

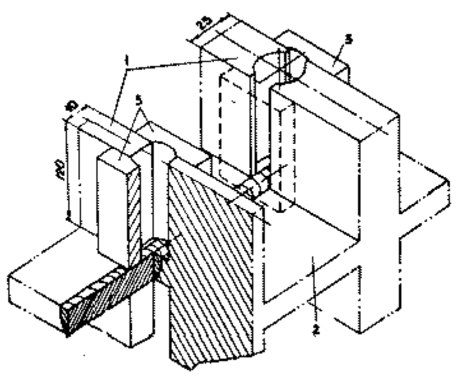


Fig. 5. Diagram of the joint groove for welding ribs with 10 mm and 25 mm thickness.

Special crystallizers 3 are set upon the butt on the sides. If butt length is 25.. 100 mm and more then welding is carried out in two stages: in the first stage a number of holes are drilled with pitch 2 (D-o) where D is a hole diameter, o is an overlap of the plug welds, and then the holes are welded up; in the second stage the holes between plug welds made in the first stage are first drilled and then welded up. The vertical rotating nonconsumable electrode welding process enabled us to automate welding of butts with an intricate section (tee, double-tee, etc.) as shown in Fig. 5. Joints made by vertical rotating nonconsumable electrode welding are characterized by small dimensions of the weld and disoriented metal structure (Fig. 6). This may explain the high values of mechanical properties of the joints (Table 2).

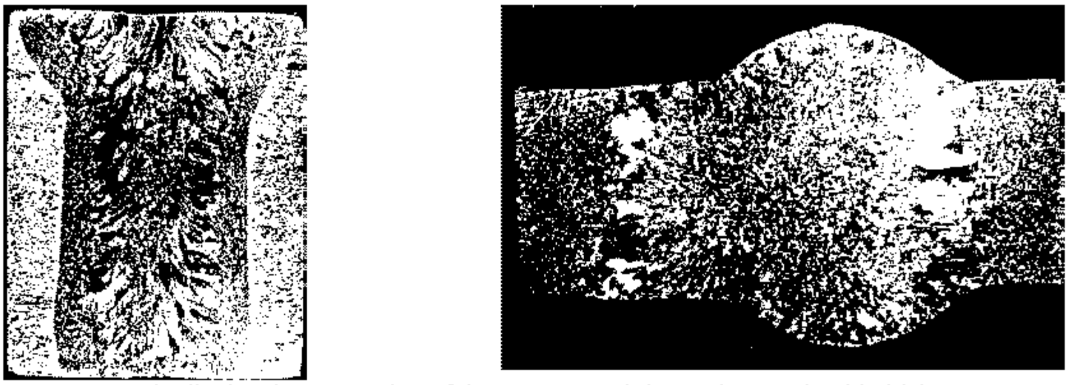


Fig. 6 Longitudinal and cross section of the component joint made VT6ch with thickness $\delta = 8$ mm and height h = 20 mm.

Table 2 Mechanical properties of joints made by VWRNE

Material (filler grade)	Specimen Condition	Ultimate Strength σ_B, MPa		Impact Toughness KCU, kJ/m^2	
		20°C	-70°C	20°C	-70°C
VNS2 steel (EP659A-VI)	as welded	1200	-	1500	1050
30CrMnSiNi2N steel (VL12DG-V1)	as welded + heat - treated	1600	1670	620	360
VT6ch titanium (SPT-2)	as welded + annealed	900	-	750	620

Note: Average values after 5 tests are presented, deviation is <. 10%

The mentioned advantages and a series of other merits of the argon-arc vertical rotating nonconsumable electrode welding, such as high density of the weld metal, insignificant welding deformation, maneuverability of the process and equipment which is especially important during welding under assembly and operating conditions as well as other advantages bring out the process to the range of the most promising ones for manufacturing complex highly loaded aircraft structures. For implementation of the vertical rotating nonconsumable electrode welding in the serial production special automatic welding heads have been designed.

4. Conclusions

1. Developed automated gas-shielded arc welding processes provide for the possibility to make quality consistent thick-walled joints of the aircraft load-carrying structures under assembly conditions.
2. A complex of new welding techniques covers practically the whole range of the aircraft welded load-carrying structural components made of high strength steels and titanium alloys joint length. For >0.5 m joint length consumable electrode narrow gap welding should be used, for 0.1 -0.5 m length - scanning nonconsumable narrow gap welding and for <0.1 m length - vertical rotating electrode welding.
3. Application of low frequency disturbances in the form of the arc transverse oscillation or rotating to the weld pool favours refining and disorientation of the weld metal structure and acquisition of high mechanical characteristics of the joint. The best result is obtained within the range of disturbance frequencies 0.9 -1.2 Hz.
4. Established analytical and experimental dependencies of the penetration depth on the welding parameters may be used for development of the automatic welding control systems.

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