FRICTION STIR WELDING IN AEROSPACE INDUSTRY (Review)

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Friction stir welding (FSW) finds ever wider application in industry, especially in manufacture of new engineering objects. In the review the examples of modern application of FSW in aerospace industry are given. They describe capabilities of the process and basic trends in development of FSW technologies existing today. The application of FSW in aerospace industry allows reducing the weight of flying vehicles, reducing number of riveted joints by 65 %, joining materials not welded using known methods, automation of joints control. 10 Ref., 7 Figures.

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Speaking about application of FSW in aerospace industry one can take data about any leading world corporations connected with manufacture of aircrafts, rockets, space stations and find numerous examples of application of this welding technology and its advantages.

Why namely FSW finds ever wider application in aerospace industry? Why world concerns contribute large funds into this technology? For example, the Boeing corporation made investments of 15 mln USD into FSW only for welding of tanks of «Delta» rocket-carriers. In the published review the author makes attempts to answer the questions and systemize the applications and basic trends for development of FSW technology existing today in aerospace industry (Figure 1).

FSW process. FSW was invented and patented in the Welding Institute (TWI) in December, 1991. TWI successfully filed the applications on patents in Europe, USA, Japan and Australia.

The principle of FSW is extremely simple (Figure 2). The cylindrical rotary tool of a specific shape with shoulders and pin in the center is submerged into the joining line of the parts subjected to welding and tightly pressed to each other. Here the amount of generated heat is sufficient for plastic welding of parts without fusion. The metal, heated up to the plastic state, is moved from the zone ahead the pin into the zone after it, then it is formed by shoulders and produces the welded joint during cooling.

Application of FSW in aerospace industry. In aerospace industry FSW finds ever more application for welding body parts, welding-on of transverse and longitudinal stiffeners and also production of:

Figure 1. First test flight of aircraft «Eclipse 500», in manufacture of which FSW was used [1]

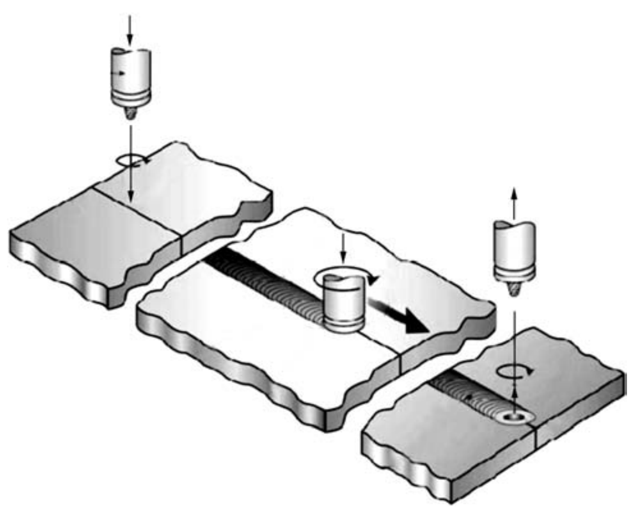

Figure 2. Scheme of FSW process according to DIN EN ISO 25239–1

• wings, fuselages, tail unit of aircrafts;
• cryogenic fuel tanks of space ships;
• fuel tanks for aircrafts;
• external fuel tanks of one-time use for military aircrafts;
• parts for rockets of military and scientific purpose.

One more field for FSW application is repair of defects of welds produced using arc welding.

The production of these design components applying FSW method is more economic as compared to the riveted joints and milling of solid metal. The welding of sheets of available materials with further shape formation is possible.

Application of FSW considerably increases compatibility of products, therefore, the information about practical applications of this welding technology and actual profits are not widely represented. However, from the materials of conferences and symposia on welding technologies [2, 3] the general representation can be obtained about advantages of use of FSW, the main of which are listed below:

• possibility of industrial manufacture of assembly units with high level of readiness;
• high level of repeatability and reproducibility and also assurance of quality at minimal deviations;
• flexibility and functional capabilities of industrial equipment allowing development of new solutions in the shortest terms.

As a rule the welded units and products in general can be verified and approved by such competent establishments like DNW, RINA and Germanescher Lloyds.

Reasons of ever wider application of FSW in aerospace industry. *Reduction of weight of flying vehicles*. The basic factor determining the ever wider application of FSW in aerospace industry is reduction of weight. The higher is the speed of the flying vehicle, the more rational is the decrease in weight. The direct proportional dependence between the weight of flying vehicles and cost-efficiency of their application can be practically established (Figure 3) [4]. The plot shows the dependence of potential savings due to economy of fuel estimating one or two dollars for gallon per 100,000 miles of way.

The economy of the aircrafts is increased due to economy of fuel. The calculation was made per 100,000 hour service life of fuselage. For the space ships the cost of pound of useful load at the orbit will amount to 20,000 USD. For the space ship «Space Shuttle» of multiple use this cost is decreased to 10,000 USD per pound.

The use of FSW during production of industrial aircraft «Eclipse 500» [5, 6] allows reducing its weight by 50 pounds. The cost of fuel for this aircraft amounts to 89 USD per pound per hour. Therefore, minimization of funds on each pound, saved in welding, estimating per 100,000 h, amounts to 7,000 USD, per 50 pounds — 350,000 USD. The same calculations can be carried out for military aircrafts.

The use of Al–Li alloys in production of fuel tanks of rocket-carriers «Space Shuttle» allowed reducing their weight by 7500 pounds which in

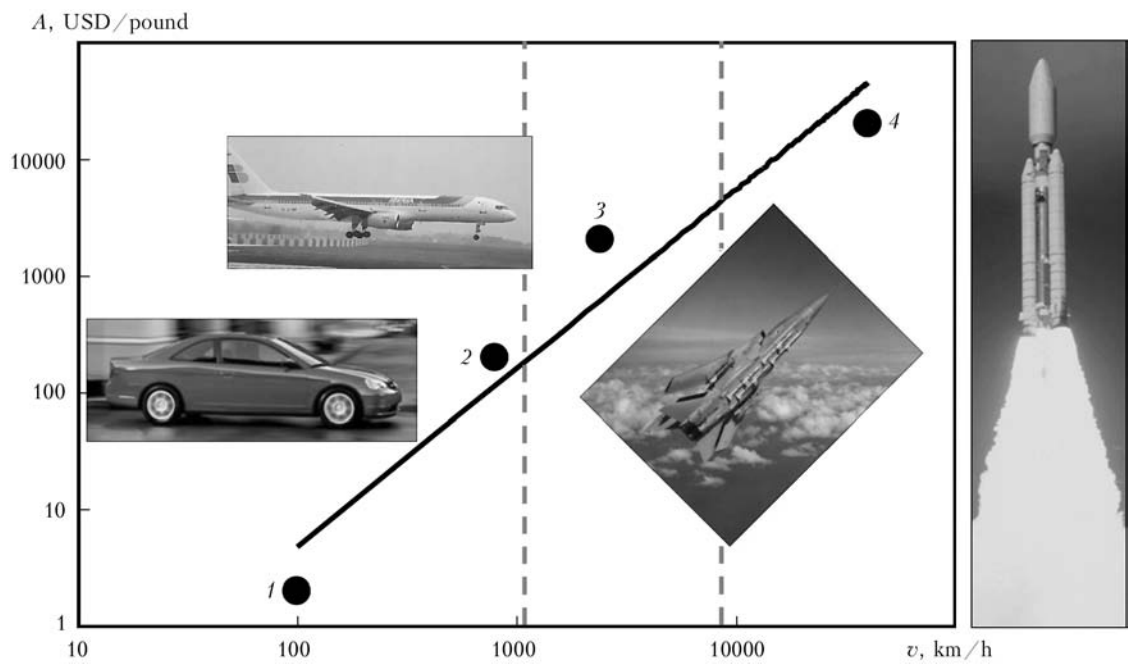

Figure 3. Effect of decreasing weight on economy of service A of motor car and aerospace engineering objects depending on the speed of their flight v [4]: *1* — motor car; *2* — aircraft; *3* — military aircraft; *4* — rocket

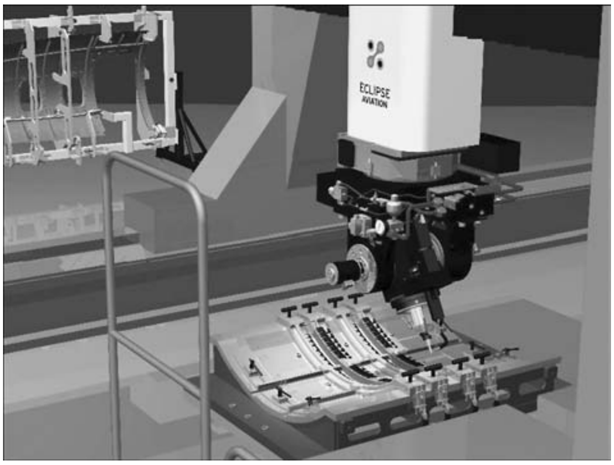

Figure 4. FSW of design components of «Eclipse 500» at the gantry machine tool (access mode: http://www.plm.automation.siemens.com/en_us/Images/Eclipse-fsw_tooling_tcm1023-21267.jpg)

financial relation means saving of 75 mln USD per a launch. This figure is determined by increase in useful load [7].

FSW: welds instead of riveted joints. Among the most important advantages of FSW in aerospace industry, the following fact can be mentioned that its application makes million of rivets redundant.

The FSW technology was at the first time applied in 2002 in production of jet aircraft «Eclipse 500» (Figures 1, 4 and 5) [6].

According to the messages from the management the application of FSW allowed 65 % decreasing the number of riveted joints. During production of each aircraft the FSW is used to weld 135 line meters of welds of cockpit, fuselage, wings and engine. FSW is applied also in the places of fastening of stiffeners and stringers. The welding is performed in automatic mode. As a result, in general 30,000 rivets are eliminated, moreover, the design performance with more rapid and simple mounting is possible. The FSW technology allows joining of design components of the aircraft body 4 times faster than automatic riveting and 20 times faster than manual one. Inner arrangement of the cockpit and saloon until the state of readiness for the flight takes not more than hour and a half. Only chairs are left to be mounted into the ready frame of the aircraft body.

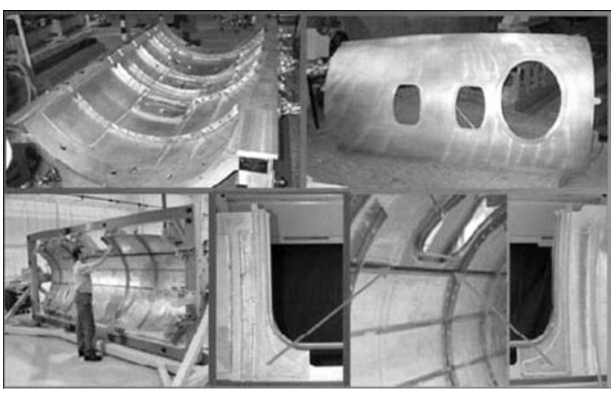

Figure 5. Elimination of riveted joints of overlapped welds using FSW (access mode: http://www.dvs-ev.de/lvmv/downloads/schweibote0207.pdf)

The time for assembly of the aircraft «Eclipse 500» from the moment of mounting the body parts into the fastening devices of FSW equipment till the moment of exit of a ready product (with engine, interior, etc.) from the gates of a hangar is reduced to 9 days. If to add here the time for industrial tests and painting works, the general time of industrial cycle from the start of the first weld till the complete readiness to take-off reaches 3 weeks.

One more important message from the Boeing is the following: FSW was successfully applied in 73 projects. The traditional welding methods are connected with application of rivets and materials-fillers, which is inevitably connected with increase in weight of flying vehicles. The Boeing uses millions of rivets. Each day it is required to drill and fill in 1.1 million holes. The cost of each hole considering expenses for design of the structure, drilling, filling in and control amounts to 5–10 USD. The cost-efficiency of FSW is obvious [8].

Application of FSW in welding of two different materials cannot be welded using other methods. Reduction of weight of flying vehicles, in production of which FSW was applied, is not so much due to the absence of rivets, but with possibility of welding aluminium alloys, which cannot be welded using other methods. Using FSW the high-strength aluminium alloys 7XXX and 2XXX can be welded. Using alloys of the higher strength the lighter components meet the requirements to strength of bodies of flying vehicles with walls of a smaller thickness and flanges of a smaller width.

Since the beginning of the 1990s the development of FSW technology is one of the reasons for ever wider spreadingof Al–Li alloys in aerospace industry as, for example, AA2195 and AA2198. Lithium has much lower specific weight as compared to aluminium and its presence reduces the mass of alloy simultaneously improving its mechanical characteristics. Al–Li alloys are used in production of fuel tanks of rocket-carriers «Space Shuttle» and «Falcon 9» (Figure 6), as well as in production of design components of fuselage of «Airbus A350 XWB».

Redundancy of expensive operations for control of welded joints. The gas arc welding is connected with fusion of metals and occurring of gas bubbles inside the welds. In its turn it requires high expenses on elimination of defects. Therefore, the Boeing, for example, decided to replace gas arc by FSW, the application of which completely eliminates the appearance of hydrogen bubbles inside the weld metal. The application of FSW eliminated the expensive X-ray control, as far as inspection of 8900 m welds produced using FSW, showed the complete absence of defects [9].

Monitoring of FSW process parameters for prevention of weld defects. The challenge of problems connected with decrease of cost and weight of flying vehicles and improvement of quality of welds is obvious. The human factor in production of rockets and aircrafts can have irretrievable consequences, therefore, one can understand thriving of producers to automate welding process and control its parameters, increasing speed of welding and considerably decreasing time of production cycle. FSW process parameters are similar to the parameters of treatment using cutting: speed of spindle rotation, feed — welding speed, thickness of parts being welded, inclination of a tool relatively to the part surface, geometry of tool and also preheating of parts and design of clamping devices.

The task of monitoring the parameters of cutting process was successfully solved in modern machine building. There is a great number of enterprises producing systems for monitoring the abovementioned parameters of cutting process and their processing centers reliably operate in the automatic lines. At any output of parameters beyond the field of tolerance the efficient actions on detection and elimination of failure reasons are provided. FSW process can be monitored using the same methods and systems applied for monitoring the parameters of cutting process.

Thus, for example, at the equipment of HAGE Sondermaschinenbau GmbH the monitoring of FSW process is carried out by control of axial load or feed speed of welding head (Figure 7).

During welding at constant load the measuring system controls the preset value of acting axial loading. The monitoring of deviation of movements from the preset values is carried out. When the tolerance is exceeded the processing center is stopped.

In welding at constant feed of welding head the welding is carried out at the constant speed as in milling. The generated forces are changed depending on uniformity of material properties. Using measuring system the monitoring of deviation of movements from the preset values is carried out. When the tolerance is exceeded the processing center is stopped.

Figure 6. Tank of rocket-carrier «Falcon 9» of Al–Li alloy (SPACEX), the longitudinal and circumferential welds of which are produced using FSW. Formation of hydrogen bubbles is completely eliminated (access mode: http://en.wikipedia.org/wiki/File: SpaceX_factoryFalcon_9_booster_tank. jpg)

The switching of monitoring modes is carried out manually or using numerical control program. For example, at the beginning and end of a weld when welding is performed at a constant force. The restricted factor of application of FSW is high axial loads and high forces of clamping of the parts being welded. Here the special clamping devices and special outfit are needed. The experience of HAGE Sondermaschinenbau GmbH for development and production of five-axial gantry processing centers for treatment of parts of steel and aluminium alloys is quite appropriate to solve this problem. The required devices for loading, clamping, feeding, unclamping and unloading of parts are designed and manufactured «key turn» at the same enterprise. The once designed clamping device guarantees the reliability during long service.

Flexibility of FSW process and simplicity of mounting the structure components after welding. The geometry of a tool, optimized to the material and shape of parts, parameters of weld-

Figure 7. Weld monitoring at the gantry center HAGEMATIC 305 FSW for processing using cutting and FSW

ing process and special outfit allow producing welds of practically any spatial configuration. One of the most convince advantages of FSW is that the design components are ready for mounting just after their welding. The expenses for grinding, polishing and straightening are eliminated.

The application of FSW allowed almost twice decreasing expenses on welding works during production of the rockets «Delta II» and «Delta IV» [10]. It is followed from the materials of report submitted to TWI from the Boeing that application of FSW during production of the rockets «Delta II» and «Delta IV» allowed decreasing their cost by 60 % and reducing period of production cycle from 23 to 6 days.

FSW is also applied to weld external tank of «Shuttle», for «Ares I» and for the stand model of «Orion Crew Vehicle» in NASA and also to weld rockets from «Falcon 1» to «Falcon 9» at SpaceX. In aircraft construction, the FSW was at the first time applied for «Boeing C-17 Globemaster III» and «Boeing 747 Large Cargo Freughter». The roofing panels of military aircraft «Airbus A400M» were also welded applying FSW.

Federal Aviation Administration approved application of FSW for assembly of aircraft «Eclipse 500» already a year earlier before the planned period.

According to the messages from the management of Airbus, the application of FSW allowed reducing the mass of welded elements of flying vehicles by 40 % and decreasing period of production cycle by 20 %.

According to the messages, for «Eclipse 500» the FSW decreases the period of production cycle and production expenses. The period of production cycle of FSW is decreased by 40 % relatively to the period of production cycle with riveted joints. Highly-automated FSW welding allows saving from 50,000 to 100,000 USD for each aircraft.

1. *http*://www.twi.co.uk
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3. *http*://techcon.ncms.org/Symposium2005/presentations/Track%202/0810%20Florence.pdf
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