THE KEY TO ECONOMY OF WELDED STRUCTURES PRODUCTION

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Abstract

A new original model of access to welded structures economic production; Design - Material - Technology - Quality model is here presented, explained and demonstrated on the practical case of GMAW (gas metal arc welding) fillet welding 4 mm steel sheets. Together 7 various methods of producing this type of joint were used. Newly experimented welding methods, firstly used on this thickness, and new equipment were applied and compared with traditional advances, using various technical-economical criteria. Various aspects were combined, with the respect to real conditions of praxis, to reach less costly, easily accessible and acceptable quality solution of this problem. The purpose of this work is to demonstrate that properly chosen and innovative experimented technology has a great influence to finished costs.

Keywords: Economic model, welded structures, GMAW, fillet weld, Rapid Arc

1.   INTRODUCTION

Weld is the most expensive part of welded structures and the basic rule to their economical production is "less welding, lower costs". However the problem is too complex to reach it with only one common advance. Input conditions vary in accordance to the type of structure, required level of quality, producer conditions, etc. that creates a wide scale of possible solutions. Every welded structure is based on simple triangle of conditions: **design - material - technology**. During the history of welding, these conditions had various importances that at various stages made one to influence other two.

1.1.   History

In the very beginning, in 40-ths of last century, the **material** was the most important and its weldability was the crucial problem that had limited all others. Now, after about 70 years research, this problem seems to be solved out for the most part of welded structures. Now-a-days there is available a great scale of easily welded materials of required properties for designers to their disposal. **Design** is the most important economic factor. Number of welds, their size and position depend only on design of welded structure. Design came to the fore especially during the first expansion of welding technology after Second World War, when a lot of products, especially castings, were rebuild to weldments, and now, in the age of automation. Welding **technology** with its permanent advance is the stable factor of costs lowering. It is known rule that the design of every welded structure should be subjected to the whole revision during every few years, in accordance to possibility of a new welding technologies application.

1.2.   New conditions

Above presented model of base conditions had dramatically changed during 90-ths when common quality assurance rules by ISO 9000 row were implemented to welding structures production. **Quality** was nominated as a main factor of welded structures design and production. In consequence of this, some of the cheapest technologies e.g. resistance welding was replaced with more expensive ones, which could offer quality assurance. Fundamental drawback was application of an old DIN code for RTG testing as the base of defects acceptance. Application of fracture mechanics that found expression in "fitness for purpose (service)" access now reduces economical damages that this sudden transformation caused.

1.3.   The present

Automation of welding is the main problem that is solving now-a-days. The main obstacle to reach high and efficient production is an old access to its solving, similar to manual welding access, especially in choosing proper wire and gas and in setting of parameters with trial-and-error method. DOE (design of experiments) statistical method of process parameters optimisation is the only way to productivity increasing. Rare examples of this access are objects of technical articles [1, 2] and usually are focused on special problem solution. Comprehensive conception is very seldom [3]. Here presented work demonstrates the new access, based on DOE statistical method of process parameters optimisation of various source-wire-gas systems and their comparison in accordance of reached weld size and other technical and economical criteria.

2.   NEW MODEL DESCRIPTION

A new model of **design - material - technology - quality** conditions (**Fig. 1**) is presented here for general solutions of welded structures production economy. This model consists with solution of three problems:
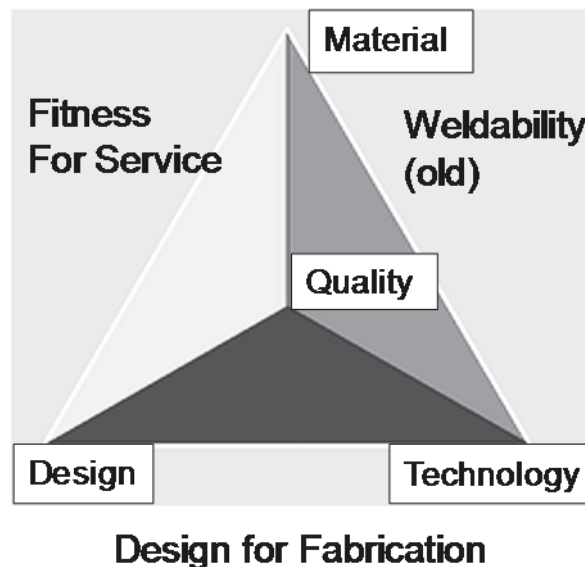

Fig. 1 Model of welded structures design and production

2.1.   Design - Material - Quality

First triangle represents choosing the right material for the design requirements. This was traditionally determined with ultimate yield strength and ultimate deformation. Now designers have a lot of other criteria, besides others based on fractural mechanic research. Crucial problem is evaluation of defects that welding accompanies and that was traditionally based on very old RTG code. This old access generates a lot of needless repairs and therefore useless increasing of costs. "Fitness for service" is the only reasonable access to choose the right material for specific structure and to evaluate accessibility of post-weld defects.

2.2.   Material - Technology - Quality

Second triangle represents material´s weldability in its old meaning, before its definition was changed in accordance to quality assurance concept. On the contrary of C-Mn steels, based on carbon and alloying elements increasing that cause worsening of weldability; the new weldable steels are based on another strengthening mechanism - micro-alloying that creates precipitational strengthening and fine-grain structure; and thermo-mechanical strengthening. These steels have, except of high strength, especially low transition temperature that guarantees their toughness at low-temperature service. Low carbon and alloying elements

content guarantee their weldability without any heat treatment - before, during and after welding. On the contrary, they require limited heat input due to conservation of their good properties. That agrees with required low stress and distortion occurrence.

2.3. Design - Technology - Quality

Third triangle represents "Design for Fabrication" access that is the domain of our research [4].
The main rules:

1) **Minimum number of welded parts** that ensures minimum number of welds. It is based on using of semi finished products, especially made with forming. Bending is cheaper and less quality damaging than welding.

2) **Minimum thickness of sheets** ensures minimum weld size. Using HSS (high-strength-steels) and AHSS (advanced HSS) we can chose material of easily welded thickness and required strength.

3) **Minimum input heat**. When we let the design and material choice on designers, the base of economy in production of welded structures is weld itself. The weld design is not so self-evident thing as it would be seemed. Of course, using modern GMAW sources, we can to choose some synergic program from machine producer. In fact, simplest solution is not cheapest. There are more ways, how to design and produce weld of the same size. Every solution requires different input heat, costs and its quality differs in accordance of many other factors, involving accessible equipment, technological discipline and level of production quality assurance. The most efficient methods are not so easily accessible. The automation and positioning are the base of workshop welding and here will be supposed as commonplace.

3. PROBLEM DEFINITION

3.1. Fillet weld specificity

In the case of fillet welds, weld size depends in a great deal on the right performance with deep penetration and low reinforcement. Overwelding is common problem that can increase costs up to 200 % [5]. Welding travel speed is the main factor not only to productivity but also to lowering of required input heat and also for reaching minimal distortion or residual stress. The reason is fact that increasing of travel speed increases melting efficiency [6] of base metal. More heat is consumed for creating of welding pool and less is lost due to conduction. Synergic effect of deeper penetration and higher welding speed makes automatic welding, under special conditions, several times more productive than manually mannered welding. Manual welding is limited with welding speed about 30 cm per minute, where melting efficiency and penetration is even 8 times lower [7] than at welding speeds, reached with modern methods.

3.2. Case study

The work, here presented, is focused on partial problem of costs, efficiency and quality of fillet weld, made with the most employed technology GMAW in automated performance on 4 mm thick steel sheets.

Commonly the weld can be produced with various processes: short arc, pulsed-arc, spray-arc, rapid-arc and other high performance techniques. It can be produced also with special low-heat wave-forming processes, using of solid or cored wire of various diameters and shielded with various gas mixtures. In this case sheet thickness 4 mm was chosen because it is out of low-heat ("cold") processes efficiency that have place for 1 - 3 mm thickness and it is still not enough to reach to high-performance processes. These are efficient for sheets over 6 mm and are the domain of our research [5].

Selecting the right conditions for this case we have chosen one shielding gas - Ferromaxx 7 (90.5% Ar, 7% CO_2, 2.5% O_2) that has proven the best properties for this thickness and considered methods. We have chosen two types of solid wires - 0.8 and 1.0 mm and two metal cored (tubular) wires 1.2 mm. Considered methods

for this case there are: short-arc as the base, most employed method for this thickness, pulsed-arc, spray arc with metal cored wire. Furthermore, a new experimental research of usability two high-performance methods is here presented: high deposited and high speed rapid-arc method and deep-penetrated short-spray method that was developed in our department. This method proved its high efficiency for sheets over 8 mm [8]. Some processes were varied with using of special FastTIP [9] equipment.

3.3   Experimental conditions

All fillet welds were performed as to be as close as possible to size of the sheet - 4 mm. That is not the same as the size of the weld *a*. Size of fillet weld **a4** assume a weld without penetration *z* and without reinforcement *r* (**Fig. 2.1**). Its deposited cross-section area is a^2 = 16 mm^2. Real weld thickness that is acceptable in accordance of standard EN ISO 25718 is fillet throat *v*. Manual welds are usually reinforced and therefore required size *a* is greater, especially when improper penetration could be expected. Well experimented automated welds that we use, have proper penetration of various depth but also expected reinforcement of various height. Hit the right required size of throat *v* during experiments is hardly accessible. Usual penetration reached with automated welding was between 0.5 and 2 mm and reinforcement below 1.0 mm. That supposes required cross-section area between 10 and 16 mm^2 in accordance to expected penetration and reinforcement.
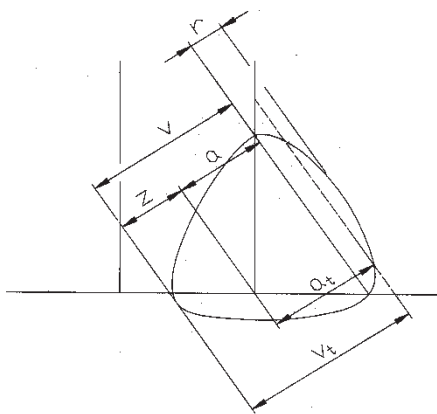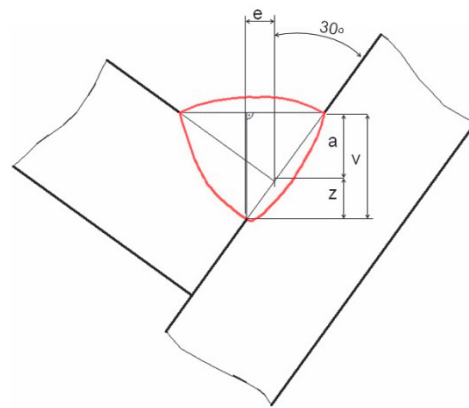

Fig. 2.1 Weld geometry

Fig. 2.2 Torch travel geometry

Fillet cross-section area is defined as the weld size squared (*a^2*) and hence every millimetre over size results in a significantly increased deposited fillet weld area **A**. Every overwelding leads to increased costs and general shrinking forces. On the other hand required deposited fillet area dramatically decreases, when penetration *z* is taken into account in computing the weld throat thickness *v* (**Fig. 2.1, 2.2**). This is particularly the case when root penetration with proper torch travel eccentricity is set and directed to the joint gap, using 30^0 torch positions (**Fig. 2.2**) as recommended with Blodgett [10] but yet not commonly used.

4.   EXPERIMENTS

Using preliminarily performed short-spray (**SS08, SS1**) and rapid arc (**RA**) statistical DOE experimental optimization, we have chosen suitable parameters for performing welds of required properties. Other classical methods where performed only with using synergic program and our experience that was based also on our preliminarily work with these methods and wires. Together seven method - gas - wire conditions with other two variants were performed.

4.1. Methods that were compared

1)   Short-arc welding (**SA**) is commonly the most widened method that can be produced with cheapest equipment, standard wire and gas. Used low current creates shallow penetration and low travel speed

means low productivity and high spatter. Benefit there is welding in all positions but at the cost of productivity. Copper-free wire 1.0 mm was used.

2) Pulse-arc welding (**PA**) is based on very smooth metal transfer without spatter but it requires better welding source and gas, with advantage of higher travel speed and deeper penetration.

3) Using metal cored wire creates smooth spray-arc process without spatter. Higher melting rate enables increasing of travel speed and greater wire diameter creates wide and flat bead. Two cored wires 1.2 mm were used. Both were developed for high speed robot welding - PZ 6102 (**T6102**) and Tubrod 14.11 (**T1411**).

4) Rapid arc (**RA**) is high deposited method based on longer stick-out (electrode extension) and sharp front torch angle. This requires shielding with high content of Argon gas and good wire feeding - with pull-push system or with short torch. Good inverter source is a main condition and the right setting of torch travel and welding parameters in accordance to preliminarily experimented parameters optimization is necessary.

5) Deep penetrated short-spray process was developed on our department and is based on increased melting efficiency of base metal that was reached with the help of DOE statistical optimization. Two diameters of wire were optimized on 4 mm sheet - 0.8 and 1.0 mm (**SS08, SS1**).

6) FastTip is contact tip that includes 10 mm insulated lead for store of resistant heating energy of wire stick-out. The benefit of this equipment should be expected in increased penetration, especially in methods, based on high melting rate and longer stick-out. Here it was used for cored wires (**T6102F, T1411F**).

4.2 Criteria for process evaluation and comparable results

Table 1 presents selected input and output parameters. The main process variables are current *I (A)* that demonstrates power density and travel speed *TS (m/min)* that determinates melting efficiency and **productivity**.

Weld **geometry** is presented with deposited cross-section area *A (mm^2)*, penetration *z (mm)*, throat *v (mm)*.

Process **efficiency** is demonstrated with specific input heat *H (kJ/cm)*. Weld **quality Q** is assessed in agreement with standard EN ISO 25718 and depends especially on the rate of reinforcement to bead width *r/w* and toe angles. Only accessible welds without defects were evaluated. Performance **demands D** (e.g. special know-how, precise set of torch travel geometry, DOE optimization) were evaluated with 1 to 3 degree (1 - low, 2 - medium, 3 - high).

Total costs assessment Σ (CZK/m) includes all factors for calculation of **1 m weld price** in Czech crowns - price of consumed wire **C**, gas **G**, work **W,** all in (CZK/m); and energy that is negligible entry.

Table 1 Comparable results of chosen set and measured variables and calculated outputs**

method	I	TS	A	z	v	H	Q	r/w	D	C	G	W	Σ*
SA	214	0.61	10.4	0.7	4.0	4.2	1	0.11	1	6.6	8.2	41.3	56.3
PA	317	0.96	10.3	0.5	4.3	5.2	1	0.12	1	6.5	5.8	25.9	38.4
T6102	322	1.33	9.9	1.9	4.4	3.1	3	0.21	1	12.4	4.2	18.7	35.3
T6102F	323	1.23	10.1	2.0	4.7	3.7	3	0.15	2	12.6	4.6	20.3	37.5
T1411	340	1.22	10.0	2.1	4.7	3.9	3	0.28	1	13.1	4.6	20.5	38.3
T1411F	337	1.24	9.9	2.9	4.5	3.9	3	0.23	2	13.0	4.5	20.2	37.8
RA	386	1.56	10.2	2.6	5.4	4.1	1	0.1	3	6.4	4.8	16.0	27.3
SS1	310	1.12	8.9	2.2	4.7	3.8	1	0.15	3	5.6	5.0	22.3	33.0
SS08	293	1.36	7.8	1.5	4.0	2.8	X	0.11	3	5.1	4.1	18.4	27.6

Σ* energy included, ** units of data are depicted above, the best input and output parameters are red coloured

4.3. Discussion

The most employed short-arc process on his maximal reached parameters at transition part to spray regime was taken as the base (100%) of our comparison. Pulsed-arc requires about 20% more heat for reaching the same throat but its productivity is about 50 % higher. Productivity of both cored wires is about twice higher but their quality is here on limited accessible level, especially bead reinforcement at T1411. Input heat is only about 75% of the base. Rapid arc, even here is operating out of its optimal regime, demonstrates highest travel speed and therefore the best productivity and surprising penetration. Earlier DOE optimization of short-spray regime with 1.0 mm wire showed its optimum for deposition cross-section area at about 12 mm^2 that is more than required. Out of this high efficient area there were found welds suitable for this case with throat over 4 mm and area under 10 mm^2. Wire 0.8 mm created narrow beads with high reinforcement that was less stable and proved changing quality. Twice more experiments had to be performed to reach DOE optimum and only a few welds reached throat over 4.0 mm. Even it has proved lowest input heat, for using in praxis we could not recommend it.

Macrostructures on **Fig. 3** (short-arc), **Fig. 4** (metal cored wire), **Fig. 5** (rapid arc) and **Fig. 6** (short-spray) demonstrate great differences in weld shape and penetration of various processes that were investigated.
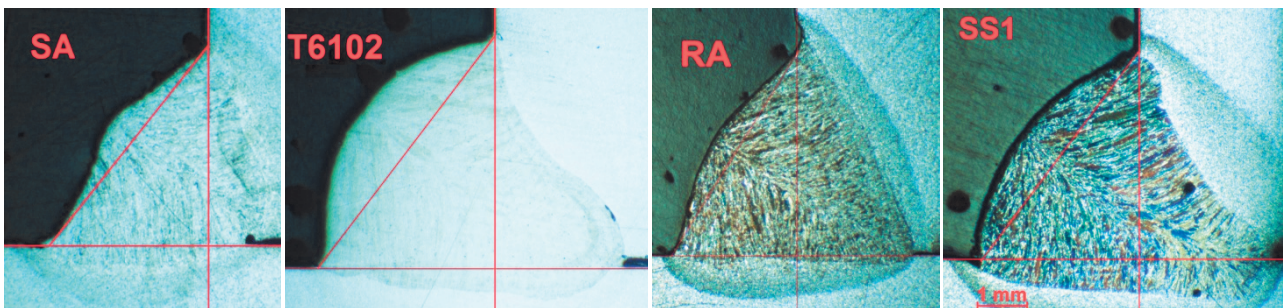

Fig. 3 Short-arc	**Fig. 4** MCW PZ 6102	**Fig. 5** Rapid Arc	**Fig. 6** Short-spray

5. CONCLUSION

Using recommended advance we have found two suitable methods for reaching highest efficiency and productivity of GMA welding fillet weld on 4 mm sheets. The easiest way is using of metal cored wire (PZ 6102), where both - low input heat and low costs are combined with easy access and minimal required preparation. Process that proved highest productivity and efficiency, Rapid arc process, needs know-how and good preparation, based on previous optimized experiments. Twice less cost as compared with usual short-arc process is bonus for this effort. So as short-spray process that needs special know-how and parameters statistical DOE optimization.

Comparing experiments that were carried out demonstrated that higher price of cored wire and 3-component gas does not play the role when price of work has decisive rate on total costs.

Every economical calculation of welded structure is based on the price of 1 m weld. As was mentioned in introduction, proper design has the greatest effect on these calculations that determine metal thickness and sum of welds length, but their size and welding travel speed that determine cost of production depend only on the right choice of technology, based on experiments, optimization of welding parameters and conditions with the respect to accessible equipment and required quality. This work demonstrates the comprehensive access to reach optimal process quality, efficiency and productivity for real input conditions that is based on previous design-process optimisation of various source-wire-gas systems and final economic comparison.

ACKNOWLEDGEMENTS

REFERENCES

[1]   GUNARAJ V., MURUGAN N. Prediction and Optimization of Weld Bead Volume for the Submerged Arc Process - Part 1. Welding Journal, Vol. 79, No. 10, 2000, Part 2. Welding Journal, Vol. 79, No. 11, 2000.

[2]   ALLEN TT., RICHARDSON RW., TAGLIABUE DP., MAUL GP. Statistical Process Design for Robotic GMA Welding of Sheet Metal. Welding Journal, Vol. 81, No. 5, 2002, pp. 69-77.

[3]   HARWIG DD. A Wise Method for Assessing Arc Welding Performance and Quality. Welding Journal, Vol. 79, No. 12, 2000.

[4]   HUDEC Z. Optimization of Source-Wire-Gas Systems for Efficient Robot Welding. IJSMDO, Vol. 4, No. 3-4, Paris, 2010, pp. 107-116.

[5]   VIWEK V., at all. Applying Lean to Welding Operations. Welding Journal, Vol. 86, No. 4, 2007, pp. 32-38.

[6]   DUPOND J N., MARDER A J. Thermal Efficiency of Arc Welding Processes. Welding Journal, Vol. 74, No. 12,1995, pp. 406- 416.

[7]   Experimental Tests of High Performance GMAW Using Air Products Shielding Gases. Technical report for Air Procucts comp., 2013. Technical University of Liberec.

[8]   Experimental Tests of High Performance Short-Spray GMAW Using Ferromaxx 7 Shielding Gas. Technical report for Air Procucts comp., 2014. Technical University of Liberec.

[9]   Alexander Binzel comp. documents.

[10]   BLODGETT OW. Design of Weldments. 8th ed., The James F. Lincoln Arc Welding Foundation, Cleveland (Ohio), 1976, Cap. 1.4 - 12.