COST EFFECTIVE DESIGN IN WELDED CONSTRUCTIONS 
PRODUCTION

Ivan Samardžić  
Marko Dundić  
Pejo Konjatić

Dr.sc. I. Samardžić, Associate Professor,  
University of Osijek, Mechanical Engineering faculty in Slavonski Brod, Trg I.B.Mažuranić  
18, 35000 Slavonski Brod  
Mr.sc. M. Dundić, Stjepana Radića 16/4, Novi Travnik, Bosna i Hercegovina  
Pejo Konjatić, dipl.ing.  
University of Osijek, Mechanical Engineering faculty in Slavonski Brod, Trg I.B.Mažuranić  
18, 35000 Slavonski Brod

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ABSTRACT

Important costs related to manufacturing of welding construction are explained in this paper. The necessity for cost effective design analysis is emphasized, from the selection of welding process and welding equipment point of view, and from the selection of welding groove and minimum welding costs point of view, also. Due to its wide range of usage in welding practice, special attention is given to main arc welding costs (human labor costs, filler material costs, energy costs, welding machine and equipment costs). Although it is rarely mentioned in professional papers, welding time calculation is very important from the welding costs point of view. Analysis of different welding costs should improve technological process and reduce costs of welding construction manufacturing.

1. INTRODUCTION

Manufacturing price of welded product is already known at world market. Manufacturer of welding constructions can exist on market only if he can offer that known or lower price. Due to fact that the manufacturing price of welding construction is conditioned by the market, manufacturer can only affect on production costs reduction to accomplish profit from production. That fact is the reason for cost effective design analysis conduction: costs reduction accomplishing the required quality, reliability and safety of product with respect to ecological principles, and principles of minimum material and energy usage also. That, for sure, causes application of new materials and new technologies, but unused possibilities and already acquired knowledge and expertises which can be used for development of technology processes and reduction of manufacturing costs of welded joints and products, should not be forgotten. Today, the application of computer technologies provides fast conduction of cost effective design analysis using own or purchased computer software packages.

2. ARC WELDING MAIN COSTS

Arc welding main costs are:
1. filler material and electric arc shield costs,
2. electric energy costs,
3. human labor costs – salary and
4. welding power source (welding machine) costs. 
Depending on type of arc welding process there are small differences in filler material and electric arc shield costs. In SMAW (Shield Metal Arc Welding) process there is no
shielding gas used in MAG/MIG and TIG welding, or welding flux used in SAW (Submerged Arc Welding) process. Other costs are calculated by the same formulas, but it is necessary to know input variables which can vary from process to process. In the following text, formulas for calculation of arc welding main costs are given.

Costs can be expressed in €/kg of deposit or in €/m of welded joint length. In this approach to welding costs, representation of costs in €/kg is adopted. For 1 m of welded joint, different quantity of deposit can be consumed and costs are proportional to deposit mass.

Deposit mass (quantity of melted filler material)
\[ G_{dep} = A \cdot l \cdot \rho, \text{ kg} \]

\( \rho \) ... density, kg/m³
\( A \) ... area of cross-section of deposit FM (groove), m²
\( l \) ... weld length, m

Deposit mass and welding costs will be reduced by reducing the area of groove cross-section in which filler material is melted and by reducing the weld length.

Theoretical welding costs will be minimal (minimum of function \( G \)), if \( A = 0 \) or \( l = 0 \), in the case where there is no welded joints. This conclusion indicates that it is necessary for designers and welding engineers to keep the values of weld thickness, groove cross-section and weld length as low as possible.

1. **Filler material and electric arc shield costs**

   \[ T_{electrode} = C_{1,electrode} \left[ \frac{\epsilon}{\text{kg electrode}} \right] \cdot k'_t \left[ \frac{\text{kg electrode}}{\text{kg deposit}} \right], \ \frac{\epsilon}{\text{kg deposit}} \]

   \( C_{1,electrode} \) - unit price of welding electrode €/kg of electrode

   \( k'_t \) - melting coefficient which express the ratio of electrode weight and coat necessary for the melting (deposition) of 1 kg deposit. This coefficient depends on electrode coat thickness, addition of metal flux in coat which is added to increase the efficiency, and of electrode residual that was left unused by welder. That scraping should be kept as low as possible and it can be from 30 to 50 mm. If enough attention is not given to this, longer scraping will cause increased costs. \( k'_t \) can have different values and can be for example, 1,7 kg electrode/kg deposit.

2. **Electrical energy costs**

   Electrical energy power:
   \[ N = \frac{U \cdot I}{1000 \cdot \eta_s} \cdot \epsilon + N_o (1 - \epsilon), \ \text{kW} \]

   Electrical energy for 1 kg deposit:
   \[ E_{kg} = \left[ \frac{U \cdot I}{1000 \cdot \eta_s} \cdot \epsilon + N_o (1 - \epsilon) \right] \cdot \frac{1}{k'_t \cdot \epsilon}, \ \text{kWh} \]
Electrical energy costs:

$$T_{el.energy} = \left[ \frac{U \cdot I}{1000 \cdot \eta_s} \cdot \varepsilon + N_0 (1 - \varepsilon) \right] \cdot \frac{I}{k_t \cdot \varepsilon} \cdot C_{el.en.} \cdot \frac{\varepsilon}{\text{kg deposit}}$$

- $U$ - electric arc voltage; approximately for SMAW, 20 - 25 V
- $I$ - welding current; approximately 40 · electrode diameter, A
- $\eta_s$ - efficiency level of weld machine is approximately for motor generator 0.55 - 0.65; for transformer 0.80 - 0.95; for rectifier 0.75 - 0.85.
- $\varepsilon$ - intermittency, burning arc time $$\varepsilon = \frac{\text{time of arc burning}}{\text{total working time (8 h for example)}}.$$

Value of $\varepsilon$ for SMAW is usually around 0.3; and only in very organized production that value can be up to 0.5. For automated welding processes higher values can be accomplished. Calculation of $\varepsilon$ value for own workshop can be performed by method of immediate observation; in random time intervals, number of arc burning on all working places is measured and compared with total number of observation.

- $N_0$ - open circuit power, when there is no arc burning. Power is then used for the ventilator work, friction, magnetic field dispersion and heating of conductors in machine. $N_0$ is approximately for the aggregates 1,0 kW; for rectifiers 0,7 kW; for transformers 0,5 kW.

- $k_t$ - melting coefficient, $\frac{g}{A \cdot h}$ or $\frac{\text{kg deposit}}{h}$ is presenting the efficiency of electrode melting and can have different values. Approximately value is around $10\frac{g}{A \cdot h}$. If welding is performed with electrode of diameter $\phi$ 4,0 mm and welding current of 160 A, then $k_t$ can be expressed in kg dep/h, also, $k_t = 160A \cdot 10 \frac{g}{A \cdot h} = 1,6 \frac{\text{kg dep.}}{h}$.

Melting coefficient depends on electrode type, amount of metal flux in electrode, material of electrode coat and welding current.

$C_{el.en.}^1$ - unit price of electrical energy €/kWh.

3. Human labor costs

$$T_{ODI} = \frac{ODI}{k_t \cdot \left( \frac{\varepsilon}{\text{kg dep.}} \right)} \cdot \frac{\varepsilon}{\text{kg dep}}$$

$ODI$ – gross amount of salary, calculated from salary by adding the obligatory taxes to social community (retirement and medical insurance and other taxes).

4. Welding machine costs

Welding machine cost calculated for work hour per year.

$$T_1 = C_N \frac{(\text{amort.} + \text{assurance} + \text{mainteance} + \text{interes rate})}{\text{total number of operating hours per year}} \cdot \frac{\varepsilon}{h}$$
\[ T_{\text{weld, mach.}} = T^1_s \left[ \frac{\varepsilon}{h} \right] \left[ \frac{1}{k_i \cdot \varepsilon} \right] \left[ \frac{h}{\text{kg dep}} \right] = \frac{C_N (\text{amort.} + \text{assurance} + \text{mainteance} + \text{interes rate})}{\text{total number of operating hours per year}}. \]

\[ \frac{1}{k_i \cdot \varepsilon}, \frac{\varepsilon}{\text{kg dep}} \]

- \( C_N \) - purchase price of machine, € or kn
- amort. - annual rate of amortization, for example, 0,1 (10% of \( C_N \) per year).
- assurance - insurance premium per year, for example, 0,01; 1% of \( C_N \)
- mainteance - annual amount necessary for maintenance, for example 0,04; 4% of \( C_N \)
- interes rate - interests rate to banks and/or taxes for business fund

**Total main costs:**

\[ T = \sum_{i=1}^{n=4} \]

For easier and faster performance of calculation and analysis of main welding costs computer program was made. In figure 1 main menu of program for calculation of main welding costs is shown.

<table>
<thead>
<tr>
<th>PROGRAM FOR ARC WELDING COSTS CALCULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Manual arc welding costs (MAW)</td>
</tr>
<tr>
<td>2. Metal active and metal inert gas welding costs (MAG/MIG)</td>
</tr>
<tr>
<td>3. Tungstem inert gas welding costs (TIG)</td>
</tr>
<tr>
<td>4. Submerged arc welding costs (SAW)</td>
</tr>
<tr>
<td>5. Different normatives and data assesment</td>
</tr>
<tr>
<td>6. Comparation of costs for different welding processes</td>
</tr>
</tbody>
</table>

**Fig. 1. Main menu of program for calculation of main costs for different arc welding processes**

**2.1 Example of main welding costs calculation**

Figure 2 shows the representation of MS Excel program interface in which data entry and calculations of main welding costs are performed.
Input data for welding costs calculation at MAW process

### a) ELECTRODE COSTS

- **Unit electrode cost (€/kg):** \( C_{\text{elektrode}} = 2.50 \)
- **Electrode fusion coefficient (kg electrode/ kg deposit):** \( k_{\text{te}} = 1.70 \)
- **Electrode cost (€/ kg deposit):** \( T_{\text{elektrode}} = 4.25 \)

### b) ELECTRIC ENERG Y COSTS

- **Welding voltage (V):** \( U = 22.00 \)
- **Welding current (A):** \( I = 160.00 \)
- **Welding machine efficiency (for rectifier 0.75 - 0.85):** \( \eta = 0.60 \)
- **Workshop intermittency (for well organized workshop is 0.3, for excellent organised workshop 0.5):** \( \varepsilon = 0.30 \)
- **Open circuit power -idling (kW):** \( N_0 = 1.00 \)
- **Specific fusion coefficient (kg deposit/h):** \( k_{\text{ts}} = 1.60 \)
- **Unit electric energy cost (electric energy cost for industry - 0.6 €/kWh):** \( C_{\text{el. energy}} = 0.60 \)
- **Electric energy cost (€/ kg deposit):** \( T_{\text{el. energy}} = 3.075 \)

### c) HUMAN LABOR COST

- **Gross amount of salary (€/h):** \( O_{\text{DIN}} = 5.00 \)
- **Personal income taxes ... (%):** \( I_{\text{ODI}} = 1.60 \)
- **Human labor cost (€/ kg deposit):** \( T_{\text{ODI}} = 16.67 \)

### d) WELDING MACHINE COST

- **Purchase price of machine (€):** \( N_c = 1500.00 \)
- **Total number of operating hours per year (h):** \( B_{\text{SR}} = 2200.00 \)
- **Obligated taxes based on purchase price of welding machine (for instance: 10% amortis., 1% assurance, 4% annual mainteance of welding machine, ...):** \( O_I = 0.15 \)
- **Welding machine cost (€/ kg deposit):** \( T_{\text{weld. machine}} = 0.213 \)

**TOTAL MAIN COSTS (€/ kg deposit):** \( T = 24.205 \)

*Fig. 2. Representation of MS Excel program interface for calculation of SMAW process costs*

Diagram of individual costs from the previous example is shown in figure 3. It is evident in this example that welders labour has the biggest influence on the total welding costs. That is mostly the case in welding of carbon structural steel, but there are some exceptions. For example, in the case when the welding is performed on expensive alloys, costs of filler material can occur as dominant costs.

Anyhow, human labour costs are high and should be reduced in order to decrease total costs. Decrease of total costs can be accomplished in several ways, and some of them are: avoiding of unnecessary over-dimension or unnecessary welding, optimal selection of welding groove, optimal selection of welding groove tolerances, appropriate selection of welding process, application of high-efficiency welding processes, application
of appropriate welding devices which will increase productivity, application of flux cored wires at MAG and SAW process etc.

Comparison of main welding costs of MAG and SAW processes for the mentioned example is shown in figure 4.

The obvious question is: Why the welding process with the lowest welding costs is not immediately selected?

In the performed calculation the lowest costs are for SAW process, and the highest for SMAW process, due to fact that melting of filler material in time unit for SAW process has the highest value, and it is predicted for every welding process time of 2200 hours per year. In the other words, by using the SAW process the highest amount of work will be achieved in the same period of time. But, equipment for SAW and MAG welding process is more expensive then SMAW welding equipment, and in this calculation, usage of equipment for at least 2200 hours per year and amortisation time of 10 years is predicted. The investment in equipment is in the beginning of its use, and the equipment will be paid off during the time of its utilisation. Calculation like this makes sense in factory with the constant need for welding, and not in the factory where welding is performed rarely and in very small amounts. In that case, profitability of SMAW process or even the utilisation of services of other factory (co-operation) should be analysed.
Comparative analysis of welding costs for MAW, MAG and SAW welding process

3. Selection of welding process and optimal welding groove

One of the criteria for the selection of economical welding process can be welding costs explained in previous passage. But, only that is not enough. There are other criteria which will, with the mentioned welding costs, condition the selection of welding process. They are:

- welding material type and thickness,
- welding position,
- quality and reliability requests,
- available equipment, welding personnel and capacity,
- time limit of construction manufacturing,
- common welding conditions etc.

Although the main arc welding processes are SMAW, MAG/MIG, TIG and SAW processes, it should be pointed out that there are many different variants of mentioned arc welding processes which are adjusted to specific types of production. Because of that it is necessary to associate the selection of welding process and optimal welding groove with specific concrete case from the practice. In most of the cases selected welding process define the shape and dimensions of welding groove. That approach is directed to minimal costs of welding construction manufacturing.

After the selection of welding process, follows the selection of optimal shape, dimensions and tolerances of welding groove. During the selection of welding groove, a few criteria should be considered:

- minimal amount of filler material,
- minimal cost of welding groove preparation (variants are: heat cutting and/or machining),
- minimal residual stress and deformations (probability of defects in manufacturing is reduced, and heat flattening is reduced or completely avoided),
- welding in the most suitable position (from the welded joint quality, productivity and work humanisation point of view),
- necessary welding devices etc.

Preparation of welding groove is performed by one of the methods of heat cutting (oxygen-flame, plasma or laser cutting), or by chip-forming machining (planing, turning operation). From the accuracy of welding groove and welding fitness point of view, machining is more desirable, but more expensive and slower. Due to that fact, it is not economical for larger needs of welding groove preparations, and it is practical only in necessary cases.

As a part of the activities on the improvement of welded product cost efficiency design, computer program for the calculation of theoretical mass of the deposited filler material was made. That program offers the possibility of comparison of different welding groove variants and graphic presentation of obtained results. For the example in figure 5, presentation of necessary filler material for the different welding groove shapes (plate thickness up to 30 mm) is shown. Preparation of each of shown welding grooves is possible with heat cutting.

On the figure 6 presentation of theoretical mass of necessary filler material for the different welding groove shapes (plate thickness from 30 to 100 mm) is given. Preparation of V and X welding groove shape is possible with heat cutting, while U and can be obtained by machining.
Cost effective design in welded constructions production

### Theoretical weld mass

![Graph showing theoretical weld mass vs. plate thickness](image)

<table>
<thead>
<tr>
<th>Welding groove type</th>
<th>V groove gouged</th>
<th>Single - V</th>
<th>Square</th>
<th>Double - V groove gouged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding groove shape</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>Presentation on diagram</td>
<td><img src="image" alt="Line" /></td>
<td><img src="image" alt="Line" /></td>
<td><img src="image" alt="Line" /></td>
<td><img src="image" alt="Line" /></td>
</tr>
<tr>
<td>Formula for calculation</td>
<td>$A = \delta^2 \cdot \pi (\frac{r}{2}) \cdot b \cdot \delta + \frac{r^2 \cdot \pi}{2}$</td>
<td>$A = (\delta - c) \cdot \pi (\frac{r}{2}) \cdot b \cdot \delta$</td>
<td>$A = b \cdot \delta$</td>
<td>$A = 0.5 \cdot \delta^2 \cdot \pi (\frac{r}{2}) \cdot b \cdot \delta + \frac{c^2 \cdot \pi}{2}$</td>
</tr>
</tbody>
</table>

**Fig. 5.** Theoretical welded joint mass (welded joint mass without bead reinforcement) for frequently used welding groove shapes depending on plate thickness (up to 30 mm)
### Theoretical weld mass

![Graph showing theoretical weld mass vs. plate thickness for different welding groove shapes.]

#### Presentation on diagram

<table>
<thead>
<tr>
<th>Welding groove type</th>
<th>Single - V</th>
<th>Double - V</th>
<th>Single - U</th>
<th>Double - U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding groove shape</td>
<td><img src="image" alt="Single-V Groove" /></td>
<td><img src="image" alt="Double-V Groove" /></td>
<td><img src="image" alt="Single-U Groove" /></td>
<td><img src="image" alt="Double-U Groove" /></td>
</tr>
<tr>
<td>Presentation on diagram</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
</tr>
<tr>
<td>Formula for calculation of theoretical weld area</td>
<td>(A = (δ - c) \cdot \frac{r}{2} + b \cdot δ)</td>
<td>(A = 0.5 \cdot (δ - c) \cdot \tan(\frac{α}{2}) + b \cdot δ + \frac{r}{2} \cdot \frac{π}{2})</td>
<td>(A = [δ - (c + r)] \cdot \tan(\frac{α}{2}) + 2 \cdot r \cdot [δ - (c + 2r)] + \frac{π \cdot r^2}{2} + b \cdot δ)</td>
<td>(A = 2 \cdot \left(\frac{c - r}{2}\right)^2 \cdot \tan(\frac{α}{2}) + 2 \cdot r \cdot [δ - (c + 2r)] + \frac{π \cdot r^2}{2} + b \cdot δ)</td>
</tr>
</tbody>
</table>

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**Fig. 6.** Theoretical welded joint mass (welded joint mass without bead reinforcement) for frequently used welding groove shapes depending on plate thickness (over 20 mm)
Figure 7 shows the influence of welding groove tolerance on theoretical mass of necessary filler material for double U welding groove shape (plate thickness is up to 60 mm).

During the definition of tolerances, desirable values which offer the possibility of high-quality welding by prescribed welding technology should be given, with the consideration of principle of minimal amount of filler material.
4. WELDING TIME CALCULATION

Complexity of welding technology is the reason of complexity of welding time calculation. Large number of welding processes, large range of main welding parameters values depending on dimensions and types of different filler materials, different welding positions and common welding conditions etc. put the difficult task on welding engineer – welding times calculation. Welding time calculation demands good knowledge of welding technology, production process and large practice expertise. That is one of the ungrateful tasks in the factories, because there is no elaborated approach to welding time calculation. There are data on amount of filler material melted in one unit of time by individual welding process, and that makes the procedure easier for the automatic welding processes. But, at semiautomatic and manual welding processes application of some special experimental methods of prediction of welding (valuation of intermittence of plant by method of immediate observation …) is necessary, valuation of time necessary for preparing and set up and production is more complicated if all conditions are not adjusted to the welder, and there is a possibility of non planned stoppages (for example waiting for crane for turning the working piece, stoppage at gaging of welded joint root, stoppage during the welding process inspection …). Factories with very large amount of welding technology make own time calculations for their production plant. Market price of welded product is depending on the quality of the welding time calculation, and time calculation can have indirect influence on the welded product quality also.

5. CONCLUSION

Cost effective design analyses are necessary to perform in all phases of welded product life cycle. Welding engineers must be guided by the idea that it is always necessary and possible to obtain the reduction of the production costs with retaining the quality level on the same or even on the higher level. During engineer analyses which should be precise and reliable, just in right time, or in the other words, speed of execution of analyses and making the valid decisions should be considered. Important role in that process have computer technologies and already developed or own computer software. In this paper, part of own cost effective design analysis activities is presented.

6. REFERENCES

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