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Welding and Cutting Costs Calculation for Structural Optimization

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Abstract: The paper describes the importance of cost calculations when we optimize a structure. These cost calculations are founded on material costs and those fabrication costs, which have a direct effect on the sizes, dimensions or shape of the structure. The cost function includes the cost of material, assembly, welding, as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. The paper describes the new cost calculations of the different technologies, considering some newer technologies like laser, plasma, water jet, etc. These costs are the objective functions in structural optimization.

Keywords: structural optimization, cost calculation, welding cost, cutting cost

1. Introduction

The paper describes that when we consider the interaction of design and fabrication technology, we should not forget about the cost as the third important characteristic of the structure. These three together help us to find the best solution. These cost calculations are founded on material costs and those fabrication costs, which have a direct effect on the sizes, dimensions or shape of the structure. Other costs, like amortization, investment, transportation, maintenance are not considered here. Sometimes we can predict the cost of design and inspection, but usually they are proportional to the weight of the structure. Cost and production time data come from different companies from all over the world. When we compare the same design at different countries, we should consider the differences between labour costs. It has the most impact on the structure if the technology is the same.

The cost function includes the cost of material, assembly, welding, as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence.

2 The cost function

The cost function of a real structure may include the cost of material, assembly, the different fabrication costs such as welding, surface preparation, painting and cutting, edge grinding, forming the geometry, etc. There are some researches have been done in this field like Klansek & Kravanja (2006a,b), Jalkanen (2007), Tímár et al. (2003), Farkas & Jármai (1997,2003,2008), Bader (2002), Mela (2013). For composites, the calculation is highly different, and there is some good information available on the internet (ArcelorMittal Profile Catalogue 2013, Cost studio 2012).

2.1 The cost of materials

$$K_M = k_M \rho V \, , \tag{1}$$

for steel, the specific material cost can be k_M=1.0-1.3 \$/kg, for aluminium it can be k_M= 3.0-3.5 \$/kg, for stainless steel it can be k_M = 6.0-7.1 \$/kg, for glass fibre it can be 20-30 \$/m^2 depending on the thickness. K_M [kg] is the fabrication cost, k_M [\$/kg] is the corresponding material cost factor, V [mm^3] is the volume of the structure, ρ is the density of the material. For steel, it is 7.85x10^{-6} kg/mm^3, for aluminium 2.7x10^{-6} kg/mm^3, for stainless steel 7.78x10^{-6} kg/mm^3, for glass fibre 2.5x10^{-6} kg/mm^3. If several different materials are used, then it is possible to use different material cost factors simultaneously in Eq. (1).

2.2 The fabrication cost in general

$$K_f = k_f \sum_i T_i \, , \tag{2}$$

where K_f [\$] is the fabrication cost, k_f [\$/min] is the corresponding fabrication cost factor, Ti [min] are production times. It is assumed that the value of k_f is constant for a given manufacturer. If not, it is possible to apply different fabrication cost factors simultaneously in Eq. (2).

a.) Fabrication times for welding

The main times related to welding are as follows: preparation, assembly, tacking, time of welding, changing the electrode, deslagging, and chipping.

b.) Calculation of the times of preparation, assembly, and tacking

The times of preparation, assembly, and tacking can be calculated with an approximation formula as follow

$$T_{w1} = C_1 \Theta_{dw} \sqrt{\kappa \rho V} \ , \qquad (3)$$

where C_1 is a parameter depending on the welding technology (usually equal to 1), Θ_{dw} is a difficulty factor, κ is the number of structural elements to be assembled. The difficulty factor expresses the complexity of the structure. Difficulty factor values depend on the kind of structure (planar, spatial), and the kind of members (flat, tubular). The range of values proposed is between 1-4 (Farkas & Jármai 1997).

c.) Calculation of real welding time

Real welding time can be calculated on the following way

$$T_{w2} = \sum_i C_{2i} a_{wi}^2 L_{wi} \ , \qquad (4)$$

where a_{wi} is weld size, L_{wi} is weld length, C_{2i} is constant for different welding technologies. C_2 contains not only the differences between welding technologies but the time differences between positional (vertical, overhead) and normal welding in downhand position, as well. The equations for different welding technologies can be found in the Farkas, Jármai (1997).

d.) Calculation of additional fabrication actions time

There are some additional fabrication actions to be considered such as changing the electrode, deslagging, and chipping. The approximation of this time is as followed

$$T_{w3} = 0.3 \sum C_{2i} a_{wi}^2 L_{wi} \ . \qquad (5)$$

In is proportional to T_{w2}. The 30% of it.

$$T_{w2} + T_{w3} = 1.3 \sum C_{2i} a_{wi}^n L_{wi} \ . \qquad (6)$$

The calculation of the times of arc-spot welding, fabrication times of post-welding treatments, time for flattening plates, surface preparation time, painting times also can be found in Farkas, Jármai (1997).

e.) Laser welding

The energy density of laser welding can be very high. The energy spectrum extends from heat conduction welding to deep-penetration welding. It is a keyhole process in which aspect ratios of up to 10:1 are attained. The benefits of high power densities with the concentrated energy input are achieving high welding speeds and the reduction of heat influence and distortion significantly. This process allows to weld a larger range of materials. The material thicknesses of up to approximately 20 mm can be welded in one pass, compared to arc welding.

Laser welding has some similar, as well as some unique characteristics compared to other welding processes, like GTAW (Gas Tungsten Arc Welding). Laser welding is a fusion process is carried out under an inert protective gas, wherein the filler is not used on most occasions. Laser welding is a high energy density beam processes like electron beam (EB) welding.

The energy is targeted directly on the workpiece. Laser differs from both GTAW and EB welding in that it does not require that the workpiece complete an electrical circuit. Since electron beam welding must be performed inside a vacuum chamber, which is a large cost. That is why laser welding can almost always offer a cost advantage over EB in both tooling and production pricing.

The pulsed laser welding offers a minimal amount of heat that is added during the process what is one of the largest advantages. A particularly small "heat affected zone" is resulting at the repeated "pulsing" of the beam, which allows cooling between each "spot" weld. This feature makes pulsed laser welding to be used for thin sections or products that require welding near electronics or glass-to-metal seals. Low heat input, combined with an optical (not electrical) process, also means greater flexibility in tooling design and materials. The speed of laser welding of steel plates can be seen on Fig. 1. For a unit length [m], the welding time [min] is the reciprocal value of the welding speed [m/min]. The value of welding time T [min] in the function of plate thickness t [mm] can be calculated this way.

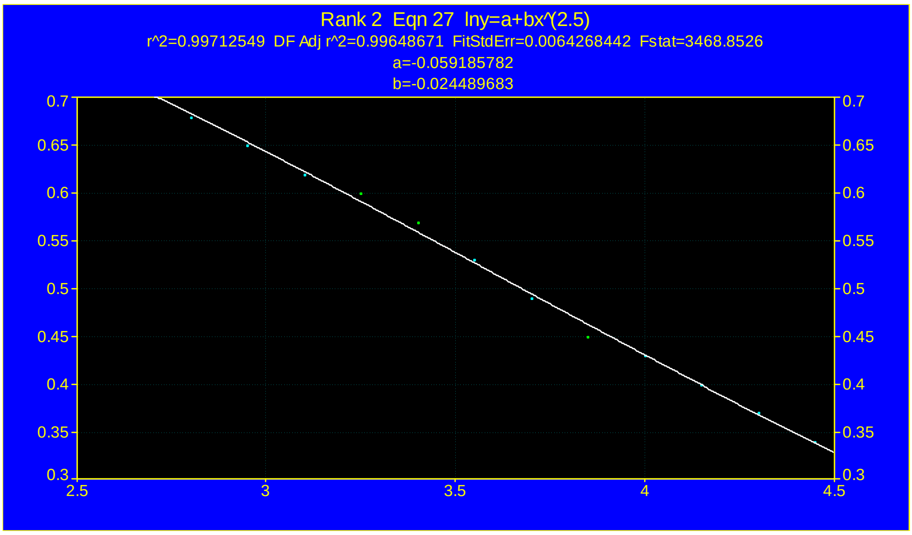

Fig. 1. Welding speed [m/min] in the function of plate thickness t [mm]

The T [min] function is as followed:

$\ln T = a + bt^{2.5}$ [min]

a= -0.05918578241974762

b= -0.02448968345282072

f.) Thermal and Water jet Cutting

The oxy-fuel gas, plasma, laser, and abrasive water jet cutting are the most commonly used non-contact methods of metal cutting. Three of them are thermal cutting processes in nature. The water jet method cuts by abrasive erosion. These processes are primarily used to make precision cuts externally and internally on flat sheet and plate material.

f1.) Plate cutting and edge grinding times

Earlier the only method was a thermal cutting one, the oxy-fuel gas cutting, using acetylene gas. The oxy-fuel torch has a pre-heating flame that heats either the iron or carbon steels to a temperature around 480° C. Then, a stream of pure oxygen is introduced causing the rapid combustion reaction between the steel and the oxygen. The resulting molten material, or slag, is blown through the metal by the stream of cutting oxygen, providing a relatively smooth and regular cut.

The cutting and edge grinding can be made by different technologies, like Acetylene, Stabilized gasmix and Propane with normal and high speed.

The cutting cost function can be formulated using in the function of the thickness (t [mm]) and cutting length (L_c [mm]). Parameters are given in Farkas, Jármai (2008):

$$T_{CP} = \sum_i C_{CPi} t_i^n L_{ci} , \tag{7}$$

where t_i is the thickness in [mm], L_{ci} is the cutting length in [mm]. The value of n comes from curve fitting calculations (TableCurve 2D 2002).

The oxy-fuel gas process in particular and most of the thermal processes share two drawbacks. First, the temperature changes in the crystal structure of the metal in the "heat-affected zone" adjacent the cut. This may reduce some of the cutting edge of metallurgical quality require pre-treatment or trimming. Second, the tolerance is less accurate than a machined cut, except for laser cutting.

f2.) Laser cutting of steel (Fig. 2) and aluminium (Fig. 3)

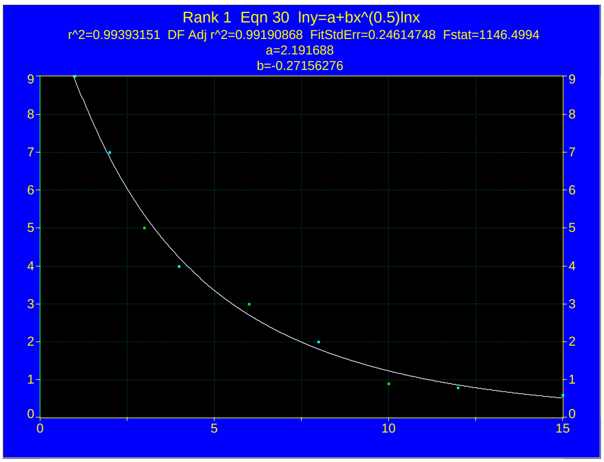

Fig. 2. Steel sheet cutting speed [length/time]

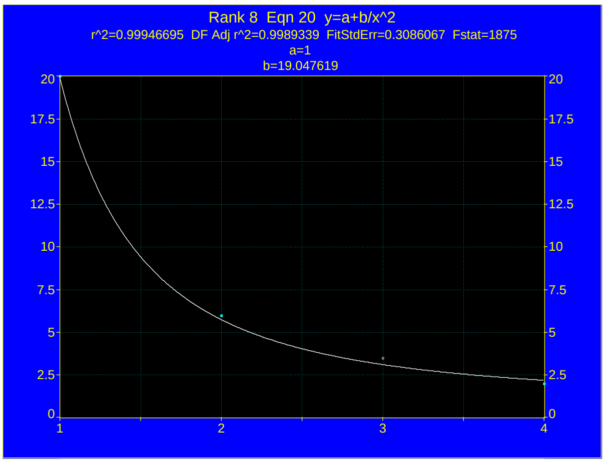

Fig. 3. Aluminium sheet cutting speed [length/time]

The T [min] functions are as follows:

Laser cutting of steel sheets	*Laser cutting of aluminium sheets*
$\ln T = a + bt^{0.5} \ln t$ [min]	$T = a + b/t^2$ [min]
a= 2.191688010897978	a= 1
b= -0.2715627600304911	b= 19.04761904761905

To cut metals and some non metallic materials with extreme precision, laser cutting is the most useful, fairly new technology for that. The laser beam is typically 0.2 mm in diameter with a power of 1-2 kW. At laser cutting process, a beam of high-density light energy is focused through a tiny hole of the nozzle. When this beam strikes the surface of the work piece, the material of the work piece is cut immediately. Lasers work best on materials such as carbon and stainless steels. Metals such as aluminium and copper alloys are more difficult to cut by laser due to their ability to reflect the laser light, as well as absorb and conduct heat. The distribution of the use of different laser manufacturing processes shown in the Fig. 4. Laser cutting is the largest application.

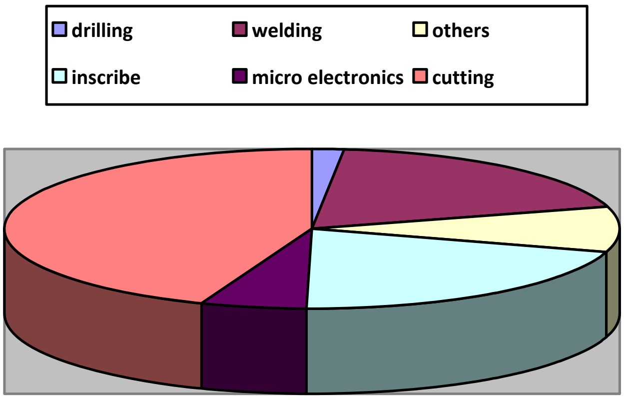

Fig. 4. Distribution of the application of laser in different manufacturing processes

f3.) Water jet cutting of steel (Fig. 5) and stainless steel (Fig. 6)

A water jet cutter is capable of cutting a wide variety of materials using an extremly high-pressure jet of water, or a mixture of water and an abrasive substance.

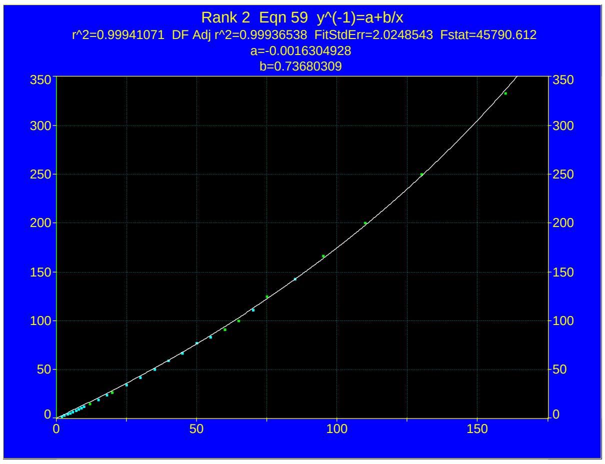

Fig. 5. Steel sheet cutting time [min]

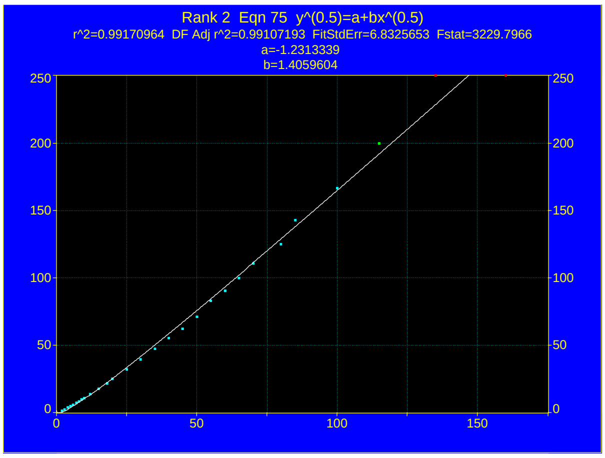

Fig. 6. Stainless sheet cutting time [min]

The T [min] functions are as follows:

Water jet cutting, carbon steel 3500 bar	*Water jet cutting stainless steel pressure 3500 bar*
$1/T=a+b/t$ [min]	$T^{0.5}=a+bt^{0.5}$ [min]
a= -0.001630492750216705	a= -1.231333913075542
b= 0.7368030917264656	b= 1.405960445076508

f4.) Plasma cutting of steel (Fig. 7) and stainless steel (Fig. 8)

Plasma cutting uses a very high temperature, high speed stream of ionized gas to cut the metal. Plasma temperatures range from about 5500 ºC to 28,000 ºC. At plasma cut, the gases used include standard compressed shop air, oxygen, argon and hydrogen, or nitrogen and hydrogen depending on the material to be cut. Gas shielding is accomplished with air, water, or carbon dioxide.

Plasma cutting requires a torch, a power supply, and an arc-starting circuit. The plasma cutting power supply is a constant-current DC power source. A high frequency AC starting circuit ionizes the gas to make it conductive. When gas is fed to the torch, part of the gas is ionized by the high-voltage arc starter between the electrode, or cathode, in the torch, and the torch tip. When the power supply’s small “dc” current meets this high voltage gas, it creates a pilot arc. This pilot arc leaves the torch tip as a plasma jet and becomes the path for the main plasma arc. Once the pilot arc contacts the metal's surface, or anode, the main arc forms. The pilot arc will be shut off and the flame cutting operations beings.

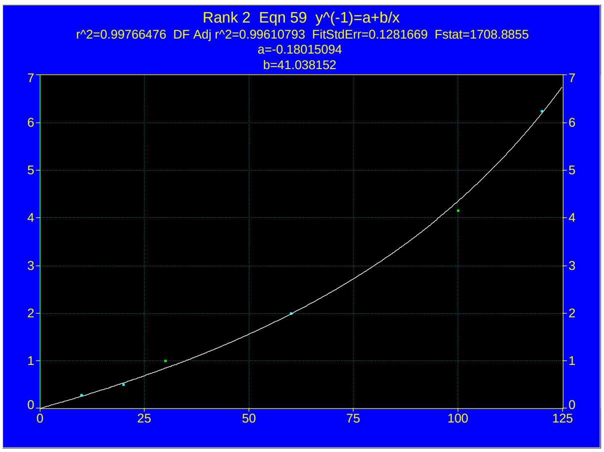

Fig. 7. Steel sheet cutting time [min]

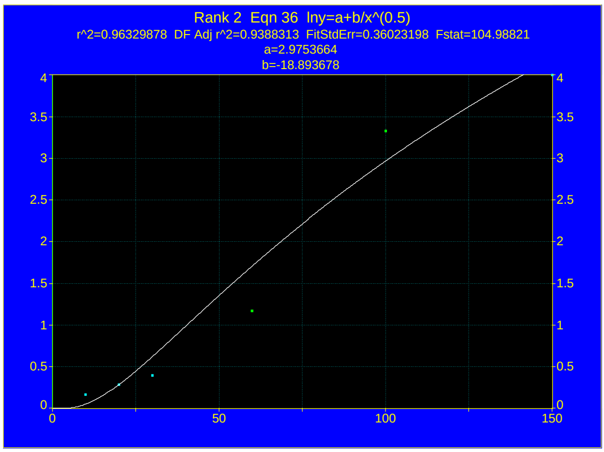

Fig. 8. Stainless sheet cutting time [min]

The T [min] functions are as follows:

Plasma cutting of stainless steel	*Plasma cutting of aluminium*
$1/T=a+b/t$ [min]	$\ln T=a+b/t^{0.5}$ [min]
a= -0.1801509431963638	a= 2.97536641707248
b= 41.03815214608195	b= -18.8936784318449

3 Conclusion

In the paper, the cost calculation of different welding and cutting technologies have been described. These cost calculations are founded on material costs and those fabrication costs, which have a direct effect on the sizes, dimensions or shape of the structure. Other costs, like amortization, investment, transportation, maintenance are not considered here. Sometimes we can predict the cost of design and inspection, but usually they are proportional to the weight of the structure. The cost function includes the cost of material, assembly, welding, as well as surface preparation, painting and cutting, edge grinding, forming the shell and is formulated according to the fabrication sequence. The calculated times for different newer technologies like laser, plasma, water jet, etc. have been done. These costs are the objective functions in structural optimization.

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