Impact of Heat Input on Mechanical Properties*

*** Adapted from an article by Juha Lukkari[1] and Olli Vähäkainu[2]**

[1] Head of Technical Service, ESAB Oy.

[2] Product Manager, Rautaruukki Steel.

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INTRODUCTION

The mechanical properties of a welded joint significantly depend on the cooling rate of the joint, and this in turn is influenced by the heat input (welding energy), plate thickness and working temperature (interpass temperature). The most significant microstructure changes from the viewpoint of the properties of the weld metal and the heat-affected zone take place during the cooling of the joint within the temperature range of 800-500ºC. It is usually the cooling time t8/5, i.e. the time required for this temperature range to be passed, which is used to describe the cooling rate.

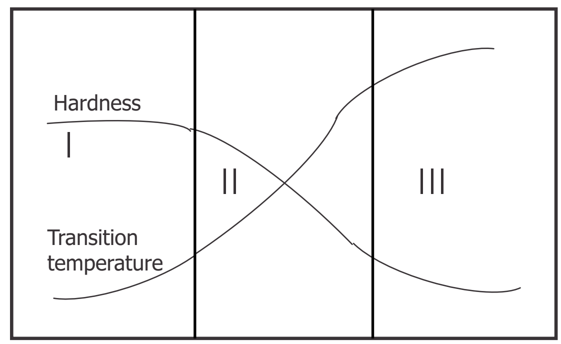

Fig. 1 : Effect of cooling time on the hardness and the impact toughness of the heat-affected zone of the welded joint

COOLING RATE AND MECHANICAL PROPERTIES

It is recognized that high heat input (kJ/cm, kJ/mm), i.e. a long cooling time t8/5 (s) weakens the mechanical properties of the joint - both its tensile strength and impact toughness. Toughness is generally more sensitive than tensile strength to high heat inputs. For example, heat input is high when the welding speed (travel speed) is low, as shown in the equation:

$$\text{Welding energy (arc energy)} = \frac{\text{Welding current x Arc voltage}}{\text{Welding speed}}$$

$$E = \frac{60 \times I\,(A) \times U\,(V)}{1000 \times v\,(mm/min)}\ (kJ/mm)$$

Heat input = thermal efficiency factor x welding energy (arc energy).

$Q = k \times E$ (kJ/mm)

Thermal efficiency factor (as per EN 1011-1):

- Submerged arc welding: 1
- MIG/MAG and MMA welding: 0.8

Figure 1 shows schematically the effect of cooling time on the hardness and impact toughness of the heat affected zone. Optimal properties will be obtained for the joint when the cooling time is within range II.

When cooling time is short, i.e. when the weld cools quickly (e.g. low heat input or considerable plate thickness), the hardness within the heat-affected zone increases greatly as does the tendency to hydrogen cracking because of hardening. On the other hand, the impact toughness properties are good, i.e. the transition temperature is low. Likewise, if the cooling time is very long, hardness will remain low but the impact toughness properties will be impaired, i.e. the transition temperature rises to higher temperatures and tensile strength may decrease.

RESTRICTIONS ON HEAT INPUT

To ensure sufficient impact toughness in the welded joint, it is necessary to restrict the maximum heat input. This maximum heat input is so much the greater, the more demanding is the particular steel's impact toughness (i.e. the lower the guarantee temperature of the impact toughness is), the higher its strength class and the smaller its plate thickness.

When the issue is that of impact toughness requirements at -40ºC or lower, for example when applying thick welds in submerged arc welding applications, then the upper limit for heat input is of the order of 3-4 kJ/mm. High heat inputs cause powerful grain size growth within the overheated heat-affected zone, immediately adjacent to the fusion line. Moreover, this causes the formation of microstructures, within the heat-affected zone, that are disadvantageous from the viewpoint of ductility; for example, grain-boundary ferrite, polygonal ferrite and side plate ferrite. Furthermore, impurities (sulphur and phosphorus) segregate to the grain boundaries, which also impairs ductility. Similar characteristics also apply to the weld metal.

Rautaruukki is, possibly, the first, steel mill in the world to have drawn up heat input graphs for its production steels. The graphs were based on the results of extensive tests in which fine-grained steels were subjected to different heat inputs for welding. Impact toughness was tested by studying different zones in the welded joints.

The lower the heat input, the more passes have to be made, and the lower, generally, is the deposition rate. This has the effect of diminishing the productivity of welding. The general aim is to use high heat inputs, which is restricted by the heat-input limits issued by the steel mill on a particular steel grade. Published heat input restrictions on steels in **Table 1** in the form of welding energy or heat input graphs is given in **Fig. 2**. Restricting heat input can also be indicated by means of cooling time $t_{8/5}$. The maximum allowable cooling times for various steel grades are mentioned in the **Table 1**.

Table 1 : Maximum values for cooling time $t_{8/5}$

Steel grade EN	$t_{8/5}$ 1) (s)	T 2) (°C)
S355J2G3 (= Fe52D)	30	-20
S355N	30	-20
S355NL	20	-40
S420N	25	-20
S420NL	15	-40
S355M	40	-20
S355ML	30	-50
S420M	35	-20
S420ML	25	-50
S460M	35	-20
S460ML	25	-50
S500M	35	-20
S500ML	25	-50

1) Cooling time $t_{8/5}$.
2) Testing temperature for impact toughness.

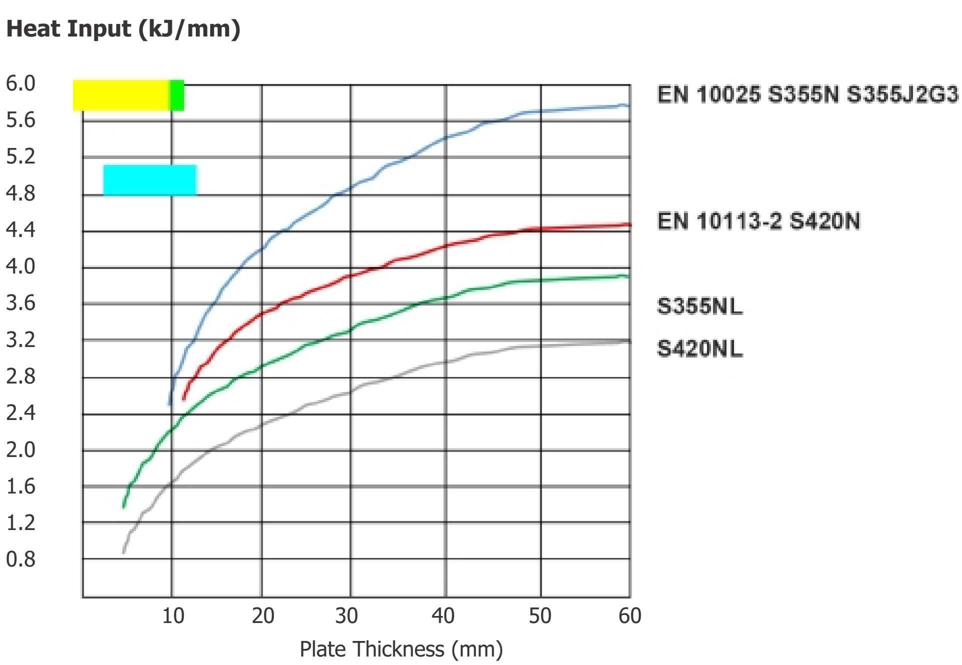

Figure 2 : Heat input limits for steels in Table 1 when welding butt joints

Since the publication of the first heat input graphs, in 1972, many studies into the effects of heat input has been conducted. On the basis of the recent tests, the heat input recommendations for the most common hot-rolled steels has been reviewed and where necessary the instructions has been reformulated. By applying the heat input recommendations it is possible to ensure maximum productivity of welding joints along with the impact toughness and tensile strength firmness requirements imposed on joints. The heat input in the tests for submerged arc welding varied between 20 and 80 kJ/cm.

Test plates were tested to determine their tensile strength by means of a transverse tensile test and their impact toughness was examined along different zones in the joint (weld metal, fusion line and heat-affected zone: fusion line + 1 mm and fusion line + 5 mm). The impact test results are presented in **Tables 3-6**, and these results are dealt with in the following. The results were good, some even surprisingly excellent. What else can one say when the entire joint withstands a heat input of 80 kJ/cm and when the impact energy persists at 100-200 J at test temperature of -50ºC!

Impact toughness of 40mm joint

The results for 40 mm TM steel plates were extremely good and they easily met the requirements of **Tables 3 and 4**.

The applied heat inputs were extremely high, 70kJ/cm and 80 kJ/cm. ENS420 M/ML and ENS460 M/ML were able to easily withstand heat inputs as high as these and the impact energy of the heat-affected zone exceeds 100 J at the test temperature of -50ºC. Even the weld metal would appear to be

Table 3 : Impact toughness of welded joints in S420 M/ML steel

Welding parameters:

- Submerged arc welding.
- Filler metals: AWS ENi2 + suitable flux
- Preheating: No.
- Interpass temperature: 50-80 ºC.
- Impact energy: mean of three tests.

Plate thickness (mm)	Joint preparation	Heat input Q (kJ/cm)	Cooling time $t_{8/5}$ (s)	Number of passed	Impact test location	Impact energy -20°C (J)	Impact energy -40°C (J)	Impact energy -50°C (J)
20	45º$_{-1/2}$-V	55	98	5	Wm	177	162	155
					Fl	179	225	198
					Fl+1	240	205	162
					Fl+5	283	274	270
					Parent material	299	299	270
					Requirement: M	min 40	-	-
					Requirement: ML	-	-	27
40	60º/90º-X	80	59	3+3	Wm	136	73	44
					Fl	207	199	185
					Fl+1	243	233	242
					Fl+5	299	229	119
					Parent Material	-	-	230
					Requirement: M	min 40	-	-
					Requirement: ML	-	-	min 27

- Wm = weld metal, Fl = fusion line, Fl+1 = fusion line + 1 mm etc.

Table 4 : The impact toughness of welded joints in S460 M/ML steel.

Welding parameters:
- Submerged arc welding.
- Filler metals: AWS ENi2 + suitable flux
- Preheating: No.
- Interpass temperature: 50-80ºC.
- Impact energy: mean of three tests.

Plate thickness (mm)	Joint prepara-tion	Heat input Q (kJ/cm)	Cooling time $t_{8/5}$ (s)	Number of passed	Impact test location	Impact energy -20°C (J)	Impact energy -40°C (J)	Impact energy -50°C (J)
20	45º$_{-1/2}$-V	55	98	5	Wm	156	112	79
					Fl	127	71	63
					Fl+1	123	149	127
					Fl+5	228	188	181
					Parent material	214	191	173
					Require-ment: M	min 40	-	-
					Require-ment: ML	-	-	min 27
40	60º/90º-X	80	59	3+3	Wm	203	157	102
					Fl	210	164	156
					Fl+1	241	207	195
					Fl+5	261	258	168
					Parent Material	-	-	326
					Require-ment: M	min 40	-	-
					Require-ment: ML	-	-	min 27

- Wm = weld metal, Fl = fusion line, Fl+1 = fusion line + 1 mm etc.

able to withstand this. In the case of steel ENS460 the value of the impact energy of the weld metal also exceeded 100 J at -50ºC.

Steel like ENS355J2G3 and their weld metals were surprisingly able to withstand heat inputs as high as 70 KJ/cm when impact resistance was tested at -20 ºC, **Tables 5 and 6**. However, the safe limit is most probably much lower than this.

It should be borne in mind that the impact toughness of the weld metal is also significantly affected by the weld structure (run sequence) and the reheating of following runs, which may be manifested in the tables for welds involving 45º-, half-V, and 60º-V grooves. In the case of a weld having a different run sequence, the impact energy value could be different, e.g. it could be lower, even if the heat input were the same.

Impact toughness of 20 mm joint

The heat input in welding TM steels was 55 kJ/cm. Steels and weld metals withstood such high heat inputs extremely well. Impact toughness was tested, at the required test temperatures, down to -50 ºC, **Table 3 and 4**.

When welding the steel ENS355J2G3 the heat input varied between 30 kJ/cm and 55 kJ/cm. The cooling times become considerably longer than when welding 40 mm plates even though the heat input is considerably lower. The maximum heat inputs appear to be excessive from the point of view of the weld metal, and the upper limit is perhaps around 45 kJ/cm with the impact test temperature being -20ºC, **Tables 5 and 6**.

The same remarks concerning the run sequence apply in this case for impact properties of the weld metal as are mentioned for 40 mm plate.

Table 5 : The impact toughness of welded joints in RAEX Multisteel.

Welding parameters:
- Submerged arc welding.
- Filler metals: AWS EM12K + suitable flux
- Preheating: No.
- Interpass temperature: 50 - 75ºC.
- Impact energy: mean of three tests.

Plate thickness (mm)	Joint preparation	Heat input Q (kJ/cm)	Cooling time $t_{8/5}$ (s)	Number of passed	Impact test location	Impact energy -0°C (J)	Impact energy -20°C (J)	Impact energy -40°C (J)
20	45º$_{-1/2}$-V	31	35	6	Wm	-	110	62
					Fl	-	101	31
					Fl+1	-	225	196
					Fl+5	-	104	45
		37	45	5	Wm	-	129	55
					FI	-	136	88
					FI + 1	-	207	160
					FI+5	-	108	66
		43	60	5	Wm	-	84	61
					FI	-	109	56
					FI+1	-	167	144
					F1+5	-	91	91
		55	98	4	Wm	-	100	57
					FI	-	111	39
					FI+1	-	179	136
					FI+5	-	79	70
-	60°-V	50	81	2+1	Wm	42	25	17
					FI	101	66	35
					FI+1	115	78	37
					FI+5	183	134	52
					Parent material	-	114	64
					Requirement: M	-	min 40	-
40	60°/90°-X	70	40	3+3	Wm 72 69 35			
					FI	111	63	35
					FI+1	80	53	27
					FI+5	105	51	27
-	45°-K	71	43	3+4	Wm	-	40	38
					FI	-	109	70
					FI+1	-	90	79
					FI+5	-	175	174
					Parent material	-	186	165
					Requirement	-	min 40	-

- Wm = weld metal, Fl = fusion line, Fl+1 = fusion line + 1 mm etc.

Table 6 : The impact toughness of welded joints in S355J2G3 steel.

Welding parameters:
- Submerged arc welding.
- Filler metals: AWS EM12K + suitable flux
- Preheating: No.
- Interpass temperature: 50 - 75ºC.
- Impact energy: mean of three tests.

Plate thickness (mm)	Joint prepara-tion	Heat input Q (kJ/cm)	Cooling time $t_{8/5}$ (s)	Number of passed	Impact test location	Impact energy -0°C (J)	Impact energy -20°C (J)	Impact energy -40°C (J)
20	45º-1/2-V	31	35	6	Wm	-	95	61
					Fl	-	112	79
					Fl+1	-	178	125
					Fl+5	-	43	19
"	"	37	45	5	Wm	-	103	58
					Fl	-	120	60
					Fl+1	-	132	52
					Fl+5	-	51	20
"	"	43	60	5	Wm	-	113	52
					Fl	-	80	44
					Fl+1	-	90	58
					Fl+5	-	74	45
"	"	55	98	4	Wm	-	73	31
					Fl	-	57	32
					Fl+1	-	112	56
					Fl+5	-	50	29
"	60º-V	50	81	2+1	Wm	48	21	13
					Fl	47	31	20
					Fl+1	55	35	25
					Fl+5	76	71	23
					Parent material:	-	43	28
					Require-ment:	-	min 27	-
40	60º/90º-X	70	40	3+3	Wm	70	56	27
					Fl	94	62	34
					Fl+1	73	45	27
					Fl+5	104	46	33
					Parent material:	-	83	-
					Require-ment:	-	min 27	-

- Wm = weld metal, FI = fusion line, FI+1 = fusion line+1 mm etc.

Heat input and plate thickness

Heat input, alone, may be misleading. Heat input should always be considered together with plate thickness. These, together with the interpass temperature, specify the cooling rate of the weld.

The tables reveal, for example, that a heat input of 80 kJ/cm with plate thickness of 40 mm gives a cooling time t8/5 of 59 s. With plate thickness of 12mm, the cooling time for the weld is the same (60 s) even though the heat input is only one-third of the above, i.e. 25 kJ/cm. Thick plates withstand considerably higher heat inputs than thin plates. This research, leads to the conclusion that, when dealing with multi-run welding of thick plates, surprisingly high heat inputs can be used in submerged arc welding applications without impact toughness properties being excessively impaired.

Strength not a problem

When transverse tensile tests were performed on welded joints, the majority of the test specimens broke on the parent material side - all the results fulfilled the requirements set on the parent material (not reported in this shortened article). Even the highest heat inputs of 70-80 kJ/cm did not soften joints to such an extent that this would have been essentially manifested in the tensile test results.

SUMMARY

As a means of reducing labour costs and of improving productivity, maximum heat input must be applied when welding. However, in order that sufficient impact toughness properties might be obtained in the welded joint, it is at times necessary to restrict the maximum heat input. The need for restriction is so much the greater, the lower the temperatures at which good impact toughness properties are required, the greater are the tensile strength requirements, and the thinner the plate being welded. The research showed that modern-day steels and welding filler metals can withstand surprisingly high heat inputs when welding thick plates and using multi-run arc welding.

In a light-hearted sense, one could say that the results for the heat-affected zones and weld metals were such that the "traditional impact toughness competition" between steel manufacturer Rautaruukki and filler manufacturer ESAB ended in a draw!