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Control of mechanical properties for high strength steels through optimized welding processes

Abstract: The cooling time between 800°C and 500°C, is a crucial factor which determines the properties of welding joints of high strength steels significantly. For field welding, the cooling time t8/5 can be steered by the heat input even if a different wall thickness for the base materials is used. Modern arc processes with reduced heat input allow comparable deposition rates and increases the stability of the strength level due to optimized equipment settings. This paper compares the influence of conventional GMAW processes like short arc, spray arc, GMAW pulse with the new launched processes like PMC (Pulse Multi Control) and others regarding the properties of the weld. Special emphasis is laid on all weld metal and joint welds. From this research, conclusions and recommendations can be derived to optimize welding properties.

Keywords: High strength steels, welding processes, welding properties

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Introduction

High strength steels are used in many areas of the industry to reduce weight and material costs. Typical applications for this kind of steel are mobile cranes, offshore platforms, concrete pumps and pressure pipelines. The advantage of TMCP (thermomechanical controlled processed) fine grain steels is to reach an optimum of strength and toughness. In general, high strength steels are used to reduce wall thickness, which leads in lower weight and the already mentioned cost savings. Due to the low carbon content, the weldability of this steels grade is good - for sure the manufactures recommendation of steel and welding consumable should be followed.

The temperature time gradient during welding and the material chemistry are crucial for the mechanical properties of high strength steels. The temperature time gradient is also described as $t_{8/5}$ time. This time is significantly responsible for the structural condition in the weld and in the heat affected zone. The $t_{8/5}$ time is the duration of the cooling down between 800 and 500 degrees Celsius.

Parameters like material thickness, weld shape, bead or layer sequence, preheating temperature and heat input influence the $t_{8/5}$ time. The heat input can be specifically controlled by the selection of the welding process. This paper compares GMAW single wire processes and GMAW Tandem-processes and their influence on mechanical properties. In particular, conventional GMAW processes like the short arc process and modified processes like GMAW

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Pulse, PMC (Pulse Multi Control), LSC (Low Spatter Control), and Tandem-processes like CMT Twin and Time Twin are surveyed.

Compared welding processes

Short arc

The short arc process has continued wire feeding. Process regulation parameters are welding voltage and welding current. As following the cycle sequence can be described: The wire is melted by the arc and a drop is formed. At the beginning of the short circuit, the drop is contacting the surface of the workpiece. To break up the short circuit and reignite the arc, a high current is needed. The surface tension of the weld pool and the high current create the so called "Pinch effect", which detaches a drop at the wire end. At the peak value of the current, the arc is reignited. High short circuit current may create extensive spatter [1].

GMAW Pulse

This process is proven and known in the industry for many years, electronically regulated power sources made it possible. The drop detachment is controlled by a material and shielding gas depending on current pulse. A short circuit free material transfer allows almost no spatter formation. The function principle is explained as follows. A liquid weld pool and a molten welding wire end is caused by the base line current level (ground current phase). Due to each rise of current (current peak), also the current density rises, the Lorenz Force will increase and the droplet is moving to the workpiece [2].

LSC (Low Spatter Control)

As already mentioned, the short arc process enables material transfer with a high current peak which leads to a possibly higher amount of spatter. High measure and control rates in the welding power source allow the LSC process to lower the current before the short circuit brake up. This stabilizes the welding performance and reduces the spatter to a minimum.

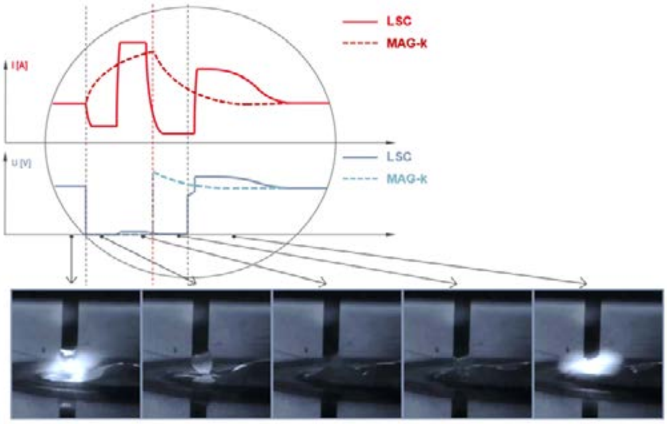

Fig. 1. Current and voltage diagram for the LSC process

PMC (Pulse Multi Control)

PMC is a further development of the GMAW Pulse process. New functions like penetration and arc length stabilizer which have been realized by a new algorithm and higher calculation speed are integrated in the welding power source. TPSi helps to control the arc in an efficient and easier way. Conventional welding machines use a constant wire feed speed. If the stickout of the welding wire is increased and the welding voltage is kept at the same level the welding current will be decreased. This results in a reduction of penetration and a higher risk for lack of fusion may occur. The "Penetration stabilizer" helps to detect variations in the stickout length and regulates according to the changes (with adjustment on the wirefeed speed). The constant welding current helps to keep the penetration on a constant level over the whole length of the weld bead. Changes

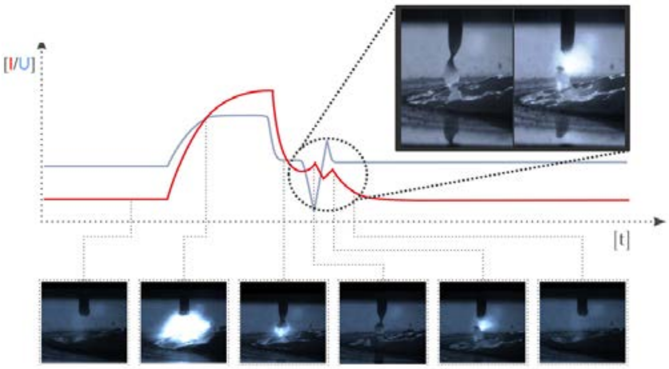

Fig. 2. Current and voltage diagram for the PMC process

in the geometrics of the weld bead or different welding speeds lead to variation in the arc length. The arc length stabilizer provides a constant arc length with a controlled short circuit during drop detachment [3].

Tandem GMAW (Time Twin)

Tandem welding (Time Twin) is using two separate welding electrodes which are molten in one weld pool. Due to the separation of the electrical potentials different arc combinations can be realized. This enables regulation of the welding speed and deposition rate

CMT Twin

Cmt (Cold Metal Transfer) was basically developed as a thin sheet metal joining process for the car industry. The main advantage of the cmt process is the low heat input due to the fact that the wire is pulled out of the liquid weld pool with an accordingly lower welding current. Cmt Twin is an upgrade of the Tandem process. Similar to the Tandem process, cmt Twin operates with two digital controlled power sources which are completely independent from each other. The system makes a large spread of the wire feed speed possible and allows the use of two cmt arcs or a mix of different arc combinations. The advantage of cmt Twin is the arc stability and the reduced heat input.

Metallurgical aspects

New optimized welding processes are created by modified electrical parameters especially the welding voltage and the welding current having a primary influence. This effect leads to variation in the heat input per unit length of weld (at a constant welding speed) and therefore it influences the mechanical properties. The use of modern welding processes enable an easier handling of the weld pool and a higher arc stability, this results in higher welding speed. All these variation possibilities give a larger process window with regards to heat input and for this reason also for the cooling time ($t_{8/5}$).

Using a modified arc process (at a comparable welding task), different mechanical properties can be expected. The lsc process, for example, reduces the welding current before the short circuit brake up which leads to a lower heat input in comparison to a conventional short arc process. This effect gives lower heat input and leads to shorter cooling time. Accordingly, the strength is higher and the ductility is decreased due to a higher content of a higher strength microstructure. Knowledge exists about these circumstances; the welding engineer can take advantage out of that.

Experimental Setup

To achieve comparable welding results, a standardized welding setup was chosen. The test was welded with a robot in pa position with m21 shielding gas (82% Argon/18%CO_2. An alform plate 700 m was used for the base material. Böhler alform® 700 mc (metal cored wire) and Böhler alform® 700 ig (solid wire) with a wire diameter of 1.2 mm were used as the welding consumable. All weld metal and V-Joint welds were surveyed, the interpass temperature for all tests was adjusted to 150°c. The test plates for all weld metal samples had a dimension of 500 mm x 150 mm and a thickness of 20 mm. An opening angle of 10° was used with a gap of 16 mm - all edges are buffered with similar material. For the V- joints, the dimensions were 700 mm × 150 mm × 20 mm. A 60° bevel angle was chosen and the root gap was 2 mm; a ceramic backing

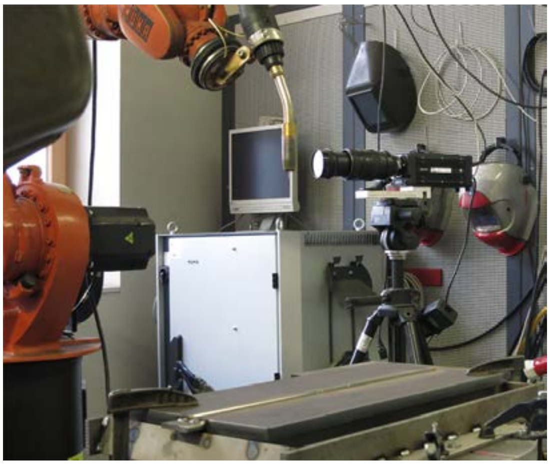

Fig. 3. Welding setup

was used. All test plates were welded in 6 layers. The V-joints were welded with 10 beads. The all weld metal included 12 beads.

Results

Results of the all weld metal

Table 1. Yield strength, tensile strength and heat input for all weld metal tests

Process	Product	$R_{p0,2}$ [MPa]	R_m [MPa]	Heat input [kJ/mm]
Standard	alform 700-IG	763	814	1.44
	alform 700-MC	736	787	1.27
PMC	alform 700-IG	785	830	1.26
	alform 700-MC	776	817	1.22
CMT-Twin	alform 700-IG	877	926	1.11
	alform 700-MC	786	828	1.05
Time-Twin	alform 700-IG	814	857	1.26
	alform 700-MC	778	814	1.19
Puls	alform 700-IG	761	817	1.57
	alform 700-MC	726	769	1.35
LSC	alform 700-IG	767	814	1.51
	alform 700-MC	727	772	1.37

The setup and the elaboration of the test samples were done according to standards EN ISO 18276 and EN ISO 16834 – in case of joint welding with adaption to Robot welding. Special emphasis was paid to the use of practical parameters also in regards to the repeatability of the weld metal joints. From all weld metal longitudinal, tensile specimens and impact specimens were taken. The impact toughness specimens were tested in a room temperature down to -40°C. Figure 4 shows the bevel preparation and sketches the specimen in the all weld metal.

All specimens fulfilled the minimum requirement according to the standard. Due to chemical differences between the solid wire (Böhler alform® 700-IG) and the metal cored wire, a higher strength level is achieved with the usage of solid wires (see table 1). The toughness values follow the common metallurgical correlation, which means higher strength leads to lower toughness values. Nevertheless, the optimized single wire GMAW processes for both products (solid wire and metal cored wire) tended to result in higher toughness values in reference to the strength modification. Homogeneous welding parameters and homogenous solidification conditions (nucleation and precipitation) might have a beneficial influence on these circumstances.

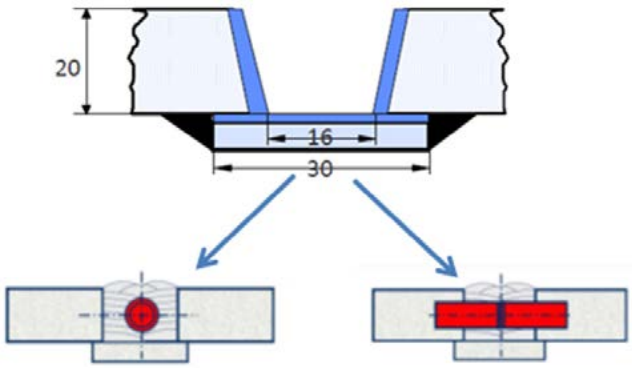

Fig. 4. Testing all weld metal

Table 1 shows the results of the tensile tests in the all weld metal. It also shows the connection between welding process and heat input. For practical reasons, the technical term heat input was used without calculation of thermal efficiency. In this respect the documented parameters of the power source were used for calculation. Hence, a practical mode of operation was possible, which is easy to follow by the user. Due to controversial discussions about the investigation of the actual heat input, especially in regards to arc efficiency on tandem wire processes, it was relinquished as well.

The better wetting ability of the metal cord wire allowed higher welding speeds which resulted in lower heat input. However, the batch causing lower strength values could not be compensated. Due to its characteristic (refer chapter *CMT Twin*), the CMT Twin process provides low heat input which leads to higher strength levels.

Table 2 shows the results of the impact tests of all weld metal. As already mentioned, the higher strength (especially with the CMT-Twin process) give lower toughness values. The optimized single wire processes tend to have better toughness and strength performance.

V-joint results

The survey matrix for V-joints covers the investigation of strength values longitudinal and transverse to the welding direction, the elaboration of longitudinal and transverse tensile samples, and toughness analyses in the weld metal as well as a hardness profile over the entire weld. Figure 5 shows the layer sequence and sample preparation.

Table 2. impact toughness for all weld metal tests

Process	Product	Impact toughness [J]		
		+20°C	0°C	-40°C
Standard	alform 700-IG	118	113	64
	alform 700-MC	137	126	97
PMC	alform 700-IG	127	118	89
	alform 700-MC	131	124	95
CMT-Twin	alform 700-IG	82	77	69
	alform 700-MC	103	96	79
Time-Twin	alform 700-IG	130	123	98
	alform 700-MC	108	104	86
Puls	alform 700-IG	133	131	94
	alform 700-MC	142	138	98
LSC	alform 700-IG	128	116	77
	alform 700-MC	152	141	108

Table 3: Yield strength, tensile strength and heat input for V-joints

Process	Product	$R_{p0,2}$ [MPa]	R_m [MPa]	Heat input [kJ/mm]
Standard	alform 700-IG	714	872	1.32
	alform 700-MC	712	806	1.25
PMC	alform 700-IG	693	895	1.24
	alform 700-MC	751	855	1.10
CMT-Twin	alform 700-IG	833	888	0.97
	alform 700-MC	824	902	0.79
Time-Twin	alform 700-IG	798	873	1.13
	alform 700-MC	757	837	1.14
Puls	alform 700-IG	739	877	1.42
	alform 700-MC	718	818	1.26
LSC	alform 700-IG	715	854	1.38
	alform 700-MC	701	810	1.27

The yield and tensile strength of the weld metal was investigated with longitudinal tensile samples according to the same procedure as described for the all weld metal. For the joints, similar parameters with practical adaption (on layer sequence) were used. Thereby no noteworthy discrepancy occurred.

Table 3 shows the results of the tensile test for the V-joints. According to the already discussed difference in the layer sequence, the welding speed was slightly increased. Hence, the heat input was reduced. The dilution with the base material is the critical factor which influences the mechanical properties significantly. Compared to all weld metal, the heat input was lower; however, the yield point was also reduced. The tensile strength followed the expected analogy according to the modified heat input. Therefore, a reduction of the yield point ratio ($R_{po,2}/R_m$) in the weld can be realized. By the use of a matched system between the base material and the welding consumable (alform® welding system), optimized results can be achieved [5].

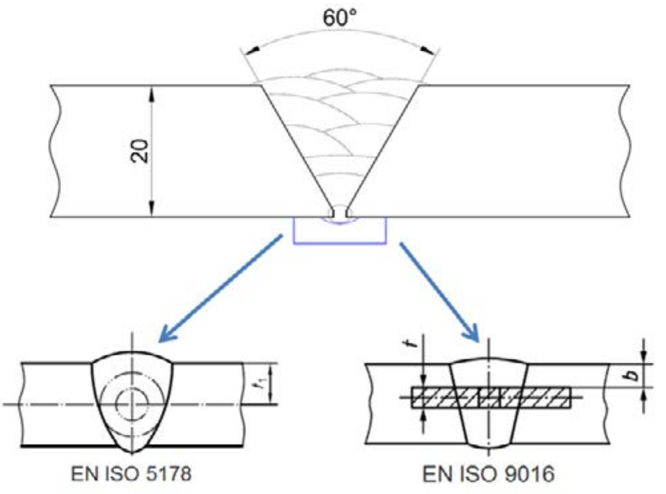

Fig. 5. Layer sequence and sample preparation for V-Joints

In particular, the toughness values in the joint welding (besides the dilution with the base material) were mainly influenced by the layer sequence. A comparison between all weld metal and V-joints has been omitted due to the multidimensional parameter variations. Alike in the survey matrix in Table 4, an explicated correlation with the welding process is not possible. To get comparable results in this case,

Table 4: Impact toughness values

Process	Product	Impact toughness [J]		
		+20°C	0°C	-40°C
Standard	alform 700-IG	170	156	101
	alform 700-MC	134	123	79
PMC	alform 700-IG	161	128	87
	alform 700-MC	116	107	69
CMT-Twin	alform 700-IG	128	113	90
	alform 700-MC	98	95	72
Time-Twin	alform 700-IG	127	113	74
	alform 700-MC	113	104	78
Puls	alform 700-IG	139	122	67
	alform 700-MC	137	120	80
LSC	alform 700-IG	160	141	83
	alform 700-MC	146	137	82

Table 5: Tensile strength and fracture location of transverse tensile samples (V-joints)

Process	Product	R_m [MPa]	**Fracture location** GW: base material SG: all weld metal
Standard	alform 700-IG	832	GW
	alform 700-MC	816	SG
PMC	alform 700-IG	898	SG
	alform 700-MC	870	SG
CMT-Twin	alform 700-IG	858	GW
	alform 700-MC	864	GW
Time-Twin	alform 700-IG	870	GW
	alform 700-MC	838	GW
Puls	alform 700-IG	846	SG
	alform 700-MC	818	SG
LSC	alform 700-IG	818	SG
	alform 700-MC	839	SG

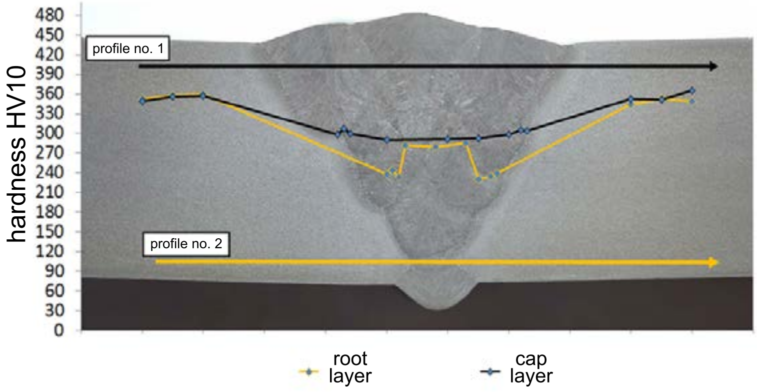

Fig. 6. Hardness profile over the weld seam -root- and cap layer for Böhler alform® 700-IG welded with the PMC process.

a different testing setup with a similar layer sequence would be necessary. Essentially is that every process reached an impact toughness of 27 J at -40°C.

Table 5 shows the evaluation of the transversal tensile strength as well as that of the fracture location. The fracture location depends on the lowest local stability in the weld or in the base material. In all cases the fracture strength is above 800 MPa.

Figure 6 shows the hardness profile over the weld seam. One hardness transverse was evaluated for the root – the other for the cap layer. In any case, the hardness of the weld metal was always around 280 HV10, which is below the values of the base material.

Summary and conclusions

Modern arc processes do not only simplify handling for the welder, they also enlarge the process window to control the mechanical properties for the welding engineer. The practical "modus operandi" (without additional measuring) was a particular focus in this paper. From a welders point of view, higher welding speed with easier arc control could be achieved which effects the heat input. Especially the V-joints which are in special focus for welding engineers show in comparison to the all weld metal an improvement for the yield point ratio. This means that a lower yield point ratio value gives a higher reliability for the components.

Remarkable, in this survey the homogenous properties concerning strength and toughness by the use of modern arc processes are presented. An improved toughness (at the same strength) can be recognized, this results in a homogenous solidification behaviour. Hence, modern arc processes do not only provide advantages for the welder (easier handling), they also influence in a positive way the formation of the weld metal microstructure. The well tested and proven alform® welding system can thus be used more flexibly and with a high safety reliability. Modern welding power sources improve welding solutions.

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