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IMPACT TESTS OF UHSS STEEL WELDED JOINTS USING THE DROP - TOWER IMPACT DROP METHOD

ABSTRACT

The article characterizes the impact test method using Drop-Tower Impact Test with the registration of the value of force and energy of breaking. Based on sources, the possibilities and scope of the current application of this method were determined and the current state of knowledge on the results of these tests was reviewed. In order to determine the possibility of using the method in impact tests of high strength steel joints, investigations of hybrid PTA - GMA welding conditions on impact strength of joints of MART S1300QL steel were carried out. In particular, the influence of $t_{8/5}$ cooling time on the impact strength of welded joints by the Drop - Tower Impact Test method was determined. It has been shown that the use of dropping machine with computer-based registration of breaking force and energy values was possible in the case of impact strength testing of UHSS welded joints and enabled precise analysis of the energy distribution dynamics absorbed by the tested.

Keywords: *Ultra High-Strength Steels, UHSS, impact strength, Dynatup, Drop-Tower Impact Test, Weldox 1300*

INTRODUCTION

The use of Drop-Tower impact machine, which allows to register the value of impact strength and energy, is an advanced, modern and effective method of conducting impact tests. What limits the scope of its usage is the high price of the device and more complex measuring process, as compared to the rival Charpy method. The Drop-Tower method, however, allows to perform other operations than just measuring impact strength, as it is the case with conventional methods of conducting impact tests. This particular method makes it possible to examine the whole process of fracturing the specimen on a graph showing the dependence between the strength and energy of the tup and time. These types of detailed tests are useful during determining the weldability of advanced structural steels [1-5]. In the test, the tup strikes the specimen vertically with a given velocity and energy (Fig. 1). During impact, both the changing value of strength and the velocity of the tup are registered at a high frequency. Depending on the object (Charpy specimen, plate or any other item), the strength and energy registered as a function of time change their character, reflecting the impact properties of a tested object.

Fig. 1. The Dynatup 9250HV drop tower impact machine: 1 – release mechanism; 2 – drop weight and tup assembly; 3 – force transducer; 4 – impactor head; 5 – guide columns; 6 – velocity detector; 7 – control panel; 8 – measurement trigger; 9 – stop block; 10 – specimen; 11 – clamp/anvil; 12 – environmental chamber; 13 – base plate

At the maximum tup drop height (1.280 m) and gravitational acceleration of 9.81365 m/s^2 (Szczecin, Poland: latitude: 53.4285438; height: 25.22 m above sea level), it is possible to obtain impact velocity of 5.01 m/s. The impact energy is described by the following dependence (1):

$$E = \frac{1}{2}mv^2 \quad (1)$$

where: E – kinetic energy of the strike, J; m – tup mass, kg, v – tup speed at the moment of impact, m/s.

When the load of the tup is within the range of $2.21 \div 25.27 \text{ kg}$, and its velocity equals 5.01 m/s, it is possible to obtain the impact energy of $65 \div 317 \text{ J}$. Velocity can be adjusted so as to obtain lower values of energy if necessary.

Drop tower impact machines are equipped with measuring modules, such as detectors of tup pressure on the specimen or a detector of tup velocity at the moment of striking the specimen; the values are registered a few thousand times per second. On the basis of the registered results, it is possible to determine the dependency between the tup velocity and time with the use of formula (2) [6]:

$$v(t) = v_0 - \int \frac{F(t)}{m} dt \quad (2)$$

where: v_0 – initial speed, $F(t)$ – load as a function of time, m – tup mass.

By integrating this expression, one obtains the displacement of the tup as a function of time $\delta(t)$ (3):

$$\delta(t) = \int v(t) dt \quad (3)$$

The change in impact energy can be calculated with the following formula (4):

$$E(t) = \int \frac{F(t) d\delta(t)}{dt} dt \quad (4)$$

Graphs generated on the basis of the above relationships allow for a detailed analysis of the behaviour of the material under dynamic loads (Fig. 2). The interpretation of both the speed and intensity of changes affecting strength and energy in relation to strain (time) is of major significance for the analysis of advanced materials. For example, in case of plastics with a layered structure, such information facilitates the optimum alignment of layers in the laminate. This, in turn, ensures the highest impact strength [7]. In some cases, one can also observe a considerable difference in the energy absorbed at plastic strain and the energy rebound as a result of elastic strain and calculate their proportions (Fig. 3).

Fig. 2. Dependence between load and time in the Drop-Tower method [8]

Fig. 3. Schematic diagram of the dependence between the impact energy of the tup and time for an elastic specimen tested with the Drop-Tower method [9]

Examples of applications the Drop-Tower impact machine

Most works in which the Drop-Tower method was employed focus on testing composites, especially laminates. The article [9] demonstrates that the impact strength in case of fibre polymer-matrix composites is highly dependent on the tup velocity and it rises significantly as the velocity increases (Fig. 4). In case of glass fibre composites, the elastic energy constitutes around 40% of maximum energy registered (Fig. 5a), which determines the material's ability to return to its original shape. In case of composites reinforced with graphite

fibre, the rebound effect does not take place at all or it is marginal. What prevails is constant increase in the energy absorbed during the initiation and propagation of the crack (Fig. 5b). Laminates consisting of layers of glass fibre connected to layers of graphite fibre exhibit intermediate impact strength characteristics when compared to the laminates reinforced exclusively with glass or graphite fibre.

Fig. 4. Dependence between load and time for a composite material with a polymer matrix reinforced with: a) glass fibre; b) graphite fibre [9]

Fig. 5. Dependence between energy and time for composite material with a polymer matrix reinforced with: a) glass fibre; b) graphite fibre [9]

The authors of article [8] analysed dynamic deformation of aluminium foams and demonstrated that reducing the thickness of the foams, lowers impact strength, which makes it possible to classify them as materials exhibiting good impact energy absorption properties in lightweight constructions.

In publication [10], researchers analysed the influence of the stamp type and strain rate on the behaviour of aluminium foam during impact test conducted with the Drop-Tower method. The authors noticed that the initial increase in the loading force acting on the specimen during impact gets more intensive as the area of the stamp decreases. In the first phase of strain, a cone-end pointed stamp applies a pressure that is three times greater than the pressure exercised by a spherical-end stamp. In the next phase of strain, a crack appears, while the loading force drops and then stabilises. In case of a spherical-end stamp, one can observe practically constant increase in the load, the value of which ultimately exceeds the maximum strength of the pointed-end stamp. Such an effect results from greater contact surface between the stamp and the material, which leads to higher frictional resistance. As far as total energy absorbed is concerned, both types of stamps display similar results, with the amount being slightly higher in case of the spherical-end stamp (Fig. 6). The relationship between the rise in stamp velocity and increased amount of energy absorbed is also distinct (Fig. 7). One can observe here the effect of hardening during the propagation of the shockwave within the

material. The value of hardening can be determined on the basis of the formula (5) by Harrigan et al. [11]:

$$\sigma_d = \sigma_{pl} + \frac{\rho_0 v^2}{\varepsilon_d} \quad (5)$$

where: σ_d – increased compressive strength caused by the shockwave,
 σ_{pl} – compressive strength in the state of *plateau*,
 ρ_0 – initial density of the foam,
 ε_d – relative strain during compression.

Another, less important, reason for a tremendous increase in the impact strength of aluminium foams at high strain rates is the sudden, dynamic compression of the air inside of them. The same phenomenon can also be observed in case of polymeric foams.

Fig. 6. The influence of the shape of a stamp on the load-displacement curve for aluminium foam tested with the Drop-Tower method [10]

Fig. 7. The influence of the stamp velocity on the impact strength of metallic foam, depending on the shape of the stamp [10]

The Drop-Weight method was also used for testing concrete reinforced with steel fibres. In article [12], it was compared with a concrete without reinforcement. The analysis of the load-strain dependence showed that the presence of fibres bears a significant influence on the strain of the material, leading to its elongation and increasing the time of contact between the tup and the specimen. The first maximum (A) appearing in the graph in the initial phase of strain corresponds to the initiation of the crack in concrete (Fig. 8). The dashed line (A-B)

shows what the graph would look like if the reinforcement in the form of steel fibres was removed. The presence of fibres leads first to a yet another rise in the pressure (C), and then to its slow decline, accompanied by elongation. Concrete, as a more rigid material, cracks first, which transfers the load on to the fibres that undergo elongation up to the C point. The value of loading force in this point can be increased by adding more fibres to the composite. As the value of the loading force grows, the fibres crack at different times, depending on their location. The differences are also due to varying degrees of fibre adhesion to concrete.

Fig. 8. Dependence between load and displacement under dynamic strain for concrete without reinforcement and concrete reinforced with steel fibres [12]

Instrumental methods of measuring the dynamics of cracking, regardless of the type of material tested, are characterized by a large dispersion of results [13]. Despite the great importance of impact strength in terms of AHSS welded joints and advanced high-performance welding processes, current research is still based on the traditional Charpy method [14-18]. Available sources lack research on the impact strength of high-strength steel under dynamic strain. The Charpy method does not provide such detailed information as the Drop-Tower one. Using the Charpy method, it has been shown that, for example, impact strength grows along with the increase of the content of retained austenite [19], [20].

In paper [11], it was experimentally proved that despite the lack of filler metals that would have the strength of at least 1100 MPa, it is possible to make a welded joint that will have the same strength as the base material or higher. The authors demonstrated that a well-matched heat input allows for such a course of phase transition that would ensure optimum microstructure of the joint. Excessive heat input leads to the growth of grains and is conducive to quenching of steel in the heat affected zone (HAZ). Reducing the heat input, however, leads to microstructure refinement and occurrence of the tempering processes, thus generating higher impact strength (Fig. 9).

Fig. 9. Influence of the heat input on the impact strength of the joints [21]

ANALYSIS OF IMPACT STRENGTH OF S1300QL STEEL WELDED JOINTS

The attempts of hybrid plasma-MAG welding were conducted on S1300QL steel. It is a MART-type steel that belongs to the group of AHSS whose CEV is 0.64, and CET is 0.409. During the welding process, the temperatures in the weld were controlled with the use of thermocouples in order to determine the cooling time in the temperature range of $800 \div 500^{\circ}\text{C}$ ($t_{8/5}$) and $800 \div 300^{\circ}\text{C}$ ($t_{8/3}$). In order to obtain a given cooling time range, different preheating temperatures and heat inputs were employed (Tab. 1). In order to obtain short cooling times, it was sometimes necessary to set the parameters at a level that did not ensure full joint penetration.

SG700 wire was used as a filler metal; it is characterised by a yield point $R_e = 680 \div 720$ MPa, ultimate strength $R_m = 740 \div 780$ MPa and elongation $A = 16 \div 18\%$. The undermatching filler metal was used for joining purposes, because it was the HAZ that was analysed. M21 gas was used as shield gas.

The impact strength tests of welded joints were conducted with the use of drop tower impact machine Instron Dynatup 9250HV in the temperature of -40°C . For each welding parameter, 3 Charpy V-notched specimens with the following dimensions were used: $55 \times 10 \times 2.5$ mm; depth of the V notch 2.0 mm. The area of the notch extended as far as 2.0 mm from the line of fusion (VHT2). The impact velocity was 4.63 m/s with the mass of a standard head being 8.3 kg. This allowed to obtain the impact energy of 90 J.

Table 1. *Welding parameters employed for a given specimen*

Parameter	Specimen number			
	1	2	3	4
Initial temperature [$^{\circ}\text{C}$]	25.8	26.5	176	20.0
Welding speed [cm/min]	70	100	70	40
Heat input [kJ/cm]	6.40	8.50	9.20	18.3
Time $t_{8/5}$ [s]	5.60	11.1	22.0	32.3
Time $t_{8/3}$ [s]	15.0	38.0	101	97.0

Results of the tests are shown in table 2; Figure 10 shows sample fracture diagrams for selected specimens (1 and 4).

Table 2. *Impact tests results*

Parameter	Specimen number			
	1	2	3	4
Time $t_{8/5}$ [s]	5.60	11.1	22.0	32.3
Strain at R_e (DEF_Re) [mm]	0.93	0.84	0.69	0.65
Strain at max. strength (DEF_peak) [mm]	1.30	1.40	1.46	1.15
Strain at cracking (DEF_crk) [mm]	3.2	3.27	3.59	1.82
Time for R_e (t_{Re}) [$s \cdot 10^{-3}$]	0.20	0.18	0.15	0.14
Time for max. strength (t_{peak}) [$s \cdot 10^{-3}$]	0.28	0.31	0.32	0.25
Time for cracking (t_{crk}) [$s \cdot 10^{-3}$]	0.72	0.73	0.81	0.40
Strength at R_e (F_{Re}) [kN]	5.01	4.77	4.84	4.71
Maximum value of strength (F_{peak}) [kN]	7.01	7.19	7.11	7.20
Strength at cracking (F_{crk}) [kN]	1.40	1.44	1.42	1.44
Energy at R_e (E_{Re}) [J]	1.45	1.44	1.23	1.09
Energy at max. strength (E_{peak}) [J]	4.58	4.81	6.27	4.31
Energy at cracking (E_{crk}) [J]	8.87	11.12	14.86	7.40
Total impact energy (E_{tot}) [J]	14.5	15.72	17.91	18.3

Fig. 10. Diagram showing the dependence between load and deflection (black curve) and between impact strength and deflection (blue curve) for specimen: a) no. 1; b) no. 4

The data shown in table 2 were statistically analysed with respect to the strength of correlation between input variables (times $t_{8/5}$, $t_{8/3}$ and heat input) and dependent variables obtained in the impact test. Table 3 shows the data obtained from the analysis of the correlations.

Figures 11 and 12 show selected statistically significant correlations.

In the course of analysis of the correlations (Tab. 3), no statistically significant correlations between inserted heat and impact test parameters were observed on the significance level of 95%. To some extent, this is the effect of difficulties in determining the amount of heat input at varying values of temperature during preheating. Cooling time proved more useful, both for the temperature range $800 \div 500^{\circ}\text{C}$ and $800 \div 300^{\circ}\text{C}$. These parameters underwent further analysis.

Figure 11 shows two correlations illustrating the drop in SWC strength as a result of extending cooling time $t_{8/5}$. The observable difference in correlation between the drop of energy until reaching the yield point and the increase in the total impact energy illustrates the phenomenon of SWC tempering. Tempering of the HAZ lowers the strength of the joint, but as it enhances its plasticity, it also improves its impact properties.

Figure 12 shows the process of diminishing the strength of the joint. As time $t_{8/3}$ extends (increasing amount of heat input), the yield point decreases. Therefore, one can observe a decline in time needed to reach both R_e and strain at R_e .

Table 3. Results of the analysis of correlation between impact test results and welding attempts parameters. Statistically significant correlations (on the level of significance of 95%) are marked with the red colour

Parameter	Independent variables		
	$t_{8/5}$	$t_{8/3}$	Qc
DEF Re	-0.969	-0.984	-0.791
DEF peak	-0.450	-0.086	-0.742
DEF crk	-0.676	-0.337	-0.912
t Re	-0.973	-0.979	-0.804
t peak	-0.414	-0.059	-0.700
t crk	-0.673	-0.333	-0.912
F Re	-0.757	-0.649	-0.765
F peak	0.636	0.518	0.679
F crk	0.589	0.464	0.647
E Re	-0.985	-0.913	-0.887
E peak	0.055	0.441	-0.356
E crk	-0.094	0.294	-0.476
E tot	0.959	0.990	0.767

Fig. 11. Graphs showing correlations between energy at yield point E_{Re} and total impact energy E_{tot} and cooling time $t_{8/5}$. The dashed line marks confidence intervals for a 95% statistical significance for the obtained regression model

Fig. 12. Graphs showing correlations between strain at the yield point DEF_{Re} and time needed to reach the yield point t_{Re} and cooling time $t_{8/3}$. The dashed line marks confidence intervals for a 95% of statistical significance of the obtained regression model

CONCLUSIONS

It proved possible to use a drop tower impact machine that can register impact strength and energy for testing AHSS welded joints. The method allowed to analyse the course of changes taking place in specimen within the time span of 2 ms in a dynamic impact test; in particular, the Drop-Tower method made it possible to investigate the dynamics of the distribution of energy absorbed by the tested steel.

The tests conducted show that cooling time in the temperature range of $800\div 500^{\circ}\text{C}$ ($t_{8/5}$) bears a considerable influence on the impact strength of S1300QL joints. The time depends mainly on the temperature of preheating and heat input. According to the research done so far [21,22], high heat input during the welding of UHSS is not recommended due to the emergence of a coarse-grain structure of the joint and release of carbides and nitrides on the grain boundaries. Such a process causes tensile strength to deteriorate.

In the above article, it was proved that expanding the $t_{8/5}$ time has a positive effect on impact strength. The moment of crack initiation turned out to be independent from welding conditions and took place at a deflection of around 1.5 mm. The value of strength at the moment of crack initiation also proved independent, remaining at a constant level of around 7.3 kN. The load corresponding to the yield point, determined geometrically on the basis of fig. 13 and 14 and shown in table 2, was increasing along with the $t_{8/5}$ time, however. The impact strength was also rising along with the extension of cooling time. The drop in energy rebound due to elastic strain that takes place for example, in case of laminates with glass fibre, was not observed. The energy curve is ascending only, which means that the energy put into breaking the specimen was consumed for the plastic strain thereof.

Fig. 13. TTT diagram for S1300QL steel; cooling curves for each specimen are marked

On the basis of the TTT diagram prepared for this steel by dilatometric tests (Fig. 13), one can observe that martensitic transformation took place in each specimen, and the curves do not contain any other transformations. However, the diversification of transformation times for individual specimens results in the appearance of martensite with varying degrees of supersaturation. In addition, longer cooling time could lead to the initiation – on a limited scale – of the processes of tempering, which bears a positive effect on the impact strength of martensitic steels.

The analysis of the results presented in the article indicates few statistically significant correlations. This is due to such factors as different velocity of the tup or changing impact point in each test. These factors are difficult to eliminate and are connected with the design of the machine per se, i.e. resistance of the moving crosshead, excess slack therein as well as inaccurate placement of the specimen in the clamp.

The accuracy of the tests could be improved by selecting a lower weight of the tup, so that the impact energy would comprise a higher range of the total energy of the tup.

However, it is the geometry of the specimen and the size of highly diversified HAZ that is of crucial importance for the result of the test. The width of the HAZ oscillates, depending on the amount of heat input, between 2 and 5 mm. The zone does not run evenly through the obtained notch, which is the result of the type and angle of bevelling employed (Fig. 14).

Fig. 14. Structure of the VHT2 notch (2 mm from the fusion line) in a 2.5 mm thick Charpy impact specimen according to the cooling time $t_{8/5}$ (for specimens 1 and 3). List of abbreviations: FZ – weld; TZ – tempered zone; SZ – soft zone; BM – base material

Depending on the thickness of the impact specimen, the notch contains a given number of zones in different proportions, including the base material. The measured impact strength is burdened with an error resulting from the geometry of bevelling. In case of the analysed 2.5 mm thick specimen, a high variety of results was obtained. Increasing the thickness of the specimen would worsen the sensitivity (resolution) of the measurement.

Another problem is finding the right location of the VHT notch due to invisibility of the fusion line on a raw specimen. If one wants to test a set of specimens thoroughly, one needs to conduct a macroscopic examination of their structure before machining – this allows to mark off the beginning of the groove notch always in the same place.

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