10th INTERNATIONAL SCIENTIFIC CONFERENCE
ON DEFENSIVE TECHNOLOGIES
OTEH 2022
Belgrade, Serbia, 13 – 14 October 2022

THE INFLUENCE OF THE HEAT INPUT ON THE IMPACT ENERGY OF THERMALLY SIMULATED HSLA STEEL WELDMENTS

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Abstract: *The paper presents the results of the influence of the amount of heat input during thermal simulation on the total impact energy, as well as the components energy of crack initiation and crack propagation energy of high-strength NIOMOL 490K steel. The influence of one-pass and two-pass HAZ simulation on the total impact energy of the tested steel was analyzed, as well as the change in the share of brittle and ductile components in the total impact energy.*

Keywords: *HSLA steel, Impact energy, Heat affected zone (HAZ), Welded Joint.*

1. INTRODUCTION

The production of modern welded steel structures requires the use of steel of increased and high strength, with increased and high yield stress, stable toughness at low and elevated operating temperatures and good weldability. The successful application of high-strength steel, NIOMOL 490K, designed for heavily loaded welded structures, used at low temperatures, depends on the properties of the critical areas of the welded joint. Heat affected zone (HAZ) and weld metal (WM) can be places of reduced impact energy with transition temperature shifted towards higher temperatures [1-4].

Introducing a new approach in the design of welded structures, and for the sake of better test efficiency, the microstructure of the area of the heat-affected zone as the most critical place of the welded joint was simulated on the HAZ simulator. Through thermal simulation, heating to a certain temperature and programmed cooling, the microstructure of different areas of the HAZ is obtained on the samples. The influence of the amount of heat input during thermal simulation on the impact characteristics, as well as the change in the share of brittle and ductile components in the total energy of the impact, were experimentally determined and analyzed in this paper [1-4].

2. EXPERIMENTAL PART

2.1. Material

The influence of HAZ simulation regime and its influence on impact characteristics has been analysed in microalloy steel of increased strength NIOMOL 490K, produced in Steel factory ACRONI" Jesenice [5]. The chemical composition and mechancal propertis, according to manufacturer, are given in Tables 1 and 2 respectively.

2.2. Heat affected zone (HAZ) simulation

The production of complex and highly responsible welded constructions implies significantly sharper criteria for acceptance of errors. At the same time, due to the importance of such constructions, a few decades ago the need for a more reliable determination of the actual mechanical properties of all zones within the heat influence zone - HAZ was clearly recognized. For this purpose, welding simulators are used.

A welding simulator is a device that achieves controlled heating and cooling, similar to that of welding. The difference is that on a sample with maximum dimensions of 15x15x60 mm, i.e. on its middle part, a microstructure with a width of about 10mm is obtained, as a microstructure that corresponds to the zone from HAZ, which enables the determination of its basic mechanical properties [4]. A schematic representation of the simulation of the HAZ of the welded joint is given in Fig. 1.

Data on the maximum temperature and cooling time Δt8/5, which represents the time it takes for the sample to cool from 800°C to 500°C, are important for the thermal cycle during heating during the simulation.

The procedure of HAZ simulation is done on simulator of thermal cycle "SMITWELD". The test samples of quartile cross section, dimensions of 11x11x55mm are used in the simulation. Prior to heating thermo-couple Ni-NiCr had been welded at the middle of test sample, in order to monitor the temperature during the simulation.

Table 1. Chemical composition of steel NIOMOL 490K [5]

Chemical composition, mass %						
C	**Si**	**Mn**	**P**	**S**	**Al**	**Cu**
0,10	0,41	0,57	0,008	0,002	0,042	0,53

Table 2. Mechanical characteristics of steel NIOMOL 490K [5]

Direction of testing	Yield strength, $R_{p0,2}$, MPa	Tensile strength, R_m, MPa	Elongation A, %	Energy of impact, ISO-V, J
L - T	565	698	27.4	253, 259, 267
T - L	561	682	24.2	212, 206, 222

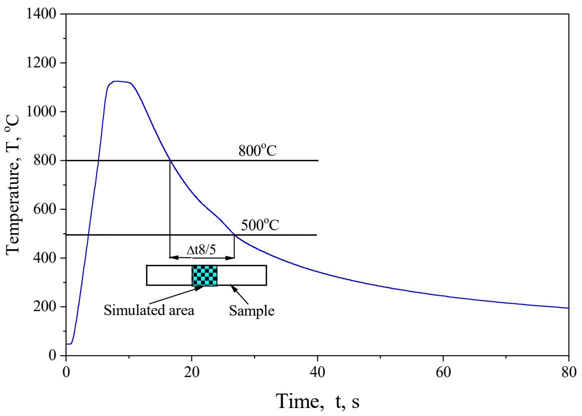

Figure 1. Simulation scheme of welded joint

Niomol 490K belongs to the group of microalloyed steels of high strength. This type of steel is welded within the cooling speed range of 8s $\leq \Delta t_{8/5} \leq$ 15s, where the lowest influence on decreasing of impact characteristics of sample with simulated HAZ microstructure is expected. The simulation of thermal conditions during welding is made by application of thermal cycles to samples of basic material [4]:

- One-pass influence with application of one cycle up to temperature $T_p \cong$1350°C (grain growth HAZ)
- Two-pass influence with application of two cycles, the first one with temperature of $T_{p1} \cong$1350°C (the grain growth HAZ is formed in such way) and the second one with temperature 700°C$\leq T_{p2} \leq$1100°C (the resistance of output grain growth HAZ shall improve or fail by transformation, either partial or fully).

The heating rate for both cases was approx. 200°C/s. The temperature of heating was kept at maximum (T_p, T_{p1}, T_{p2}) during the time of 3s (in order to heat the whole cross section of sample), and cooling rate, i.e. $\Delta t_{8/5}$ was changed from 5s for group A, 10s for group B, 20s for group C, 40s for group D up to 80s for group E. The samples from group B (15 pieces) are tested at various temperatures, whilst other groups are tested at room temperature (20°C).

In all two-pass samples HAZ, the first thermal cycle was $T_{p1} \cong$1350°C, whilst for second group of samples F was 1100°C, for group of samples G was 980°C, for group of samples H was 880°C, for group of samples I was 780°C, for group of samples J was 700°C. The cooling time for groups of samples F, G and H was 10s for the first thermal cycle and 10s for the second thermal cycle, while in groups of samples I and J was 10s for the first thermal cycle and 20s for the second thermal cycle. Scheme of thermal cycle of one-pass HAZ is shown in Fig. 2., and two-pass HAZ in Fig. 3 [4].

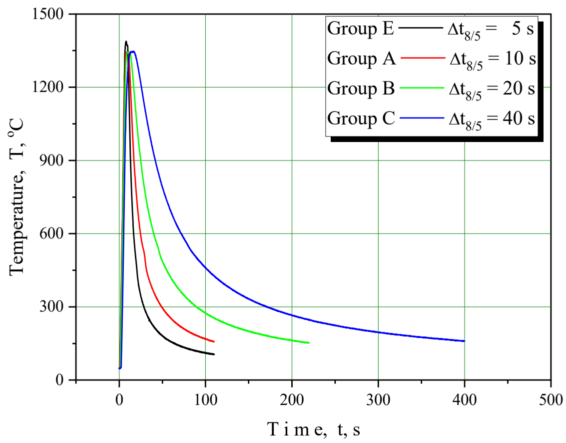

Figure 2. Thermal cycle of one-pass HAZ test samples A1, B1, C1 i D1.

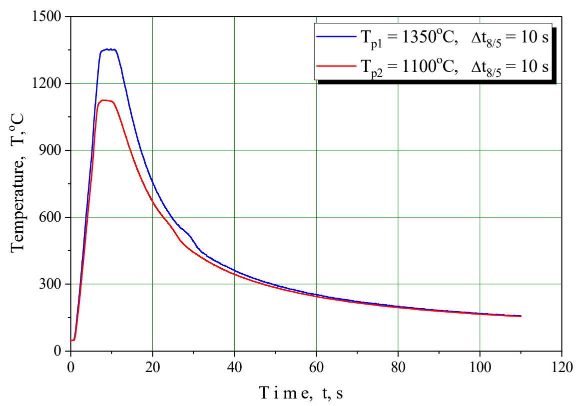

Figure 3. Thermal cycle of two-pass HAZ test samples F1.

2.3. Impact testing

Impact testing of samples is made in purpose of impact energy determination (resistance to impact). The process of testing is defined accordingly to EN ISO 148 [6] standard. Following completion of simulation the test samples dimensions of 11x11x55 mm, are processed on standard dimensions of 10x10x55 mm withV2 notch. The testing itself is done on pendulum hammer with modern instruments AMSLER 150/300 J.

3. RESULTS AND DISCUSSION

The results of impact tests are given in tab. 3 (one-pass HAZ) for test specimens of groups A, B, C, D and E that were tested at different cooling times and at a temperature of 20°C, tab. 4 (one-pass HAZ) for test specimens of group B, which were tested at different temperatures and the same cooling times, and tab. 5 (two-pass HAZ) for specimenss of groups F, G, H, I and J.

Table 3. Impact testing results of test samples of one-pass simulated HAZ

Samples mark	Testing temp., °C	Cooling time $\Delta t_{8/5}$, s	Total impact energy, $A_{tot.}$, J	Crack initiation energy, A_I, J	Crack propagation energy, A_P J
A1	+20	5	134	50	84
A2			108	48	60
A3			85	40	45
B7	+20	10	40	22	18
B8			33	20	13
B9			35	21	14
C1	+20	20	29	29	-
C2			24	24	-
C3			22	22	-
D1	+20	40	20	20	-
D2			22	22	-
D3			19	19	-
E1	+20	80	22	22	-
E2			16	16	-
E3			19	19	-

Table 4. Impact testing results of test samples of one-pass HAZ simulation

Sample mark	Testing temp., °C	Cooling time $\Delta t_{8/5}$, s	Total impact energy, $A_{tot.}$, J	Crack initiation energy, A_I, J	Crack propagation energy, A_P J
B1	-20	10	14	14	-
B2			17	17	-
B3			19	19	-
B4	0	10	24	20	4
B5			27	21	6
B6			29	21	8
B7	+20	10	40	22	18
B8			33	20	13
B9			35	21	14
B10	+40	10	67	33	34
B11			59	30	29
B12			63	31	32
B13	+60	10	85	40	45
B14			82	39	43
B15			76	37	39

As the test was performed on an instrumented Charpy pendulum, it was possible to give an assessment of how the impact (impulse) effect affects the impact characteristics, and an assessment of the plasticity of the tested material.

Two dependencies were obtained by the test: force-time and energy-time. The influence of cooling time on impact characteristics is shown in fig. 4 to 8. Due to the scope of the experiment, only one diagram from each test group is shown.

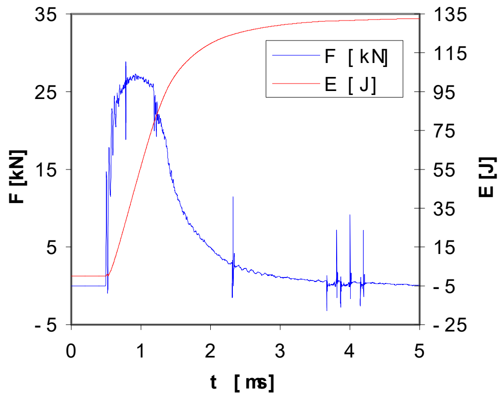

Figure 4. Specimen A1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 5s, Temp.: +20 °C, $A_{tot.}$: 134J

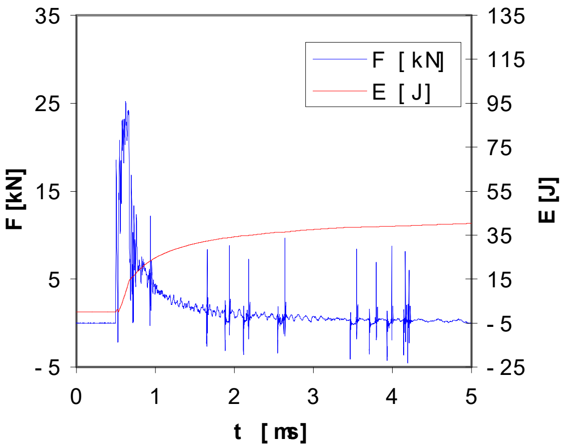

Figure 5. Specimen B1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: +20 °C, $A_{tot.}$: 40J

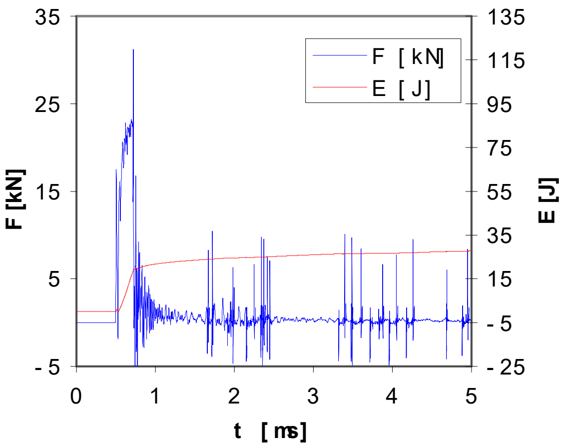

Figure 6. Specimen C1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 20s, Temp.: +20 °C, $A_{tot.}$: 29J

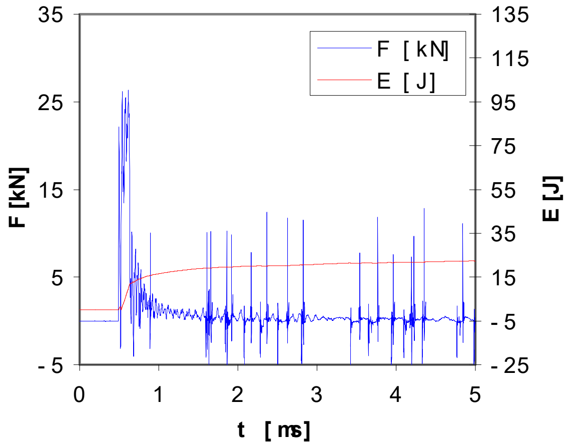

Figure 7. Specimen D1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 40s, Temp.: +20 °C, $A_{tot.}$: 24J

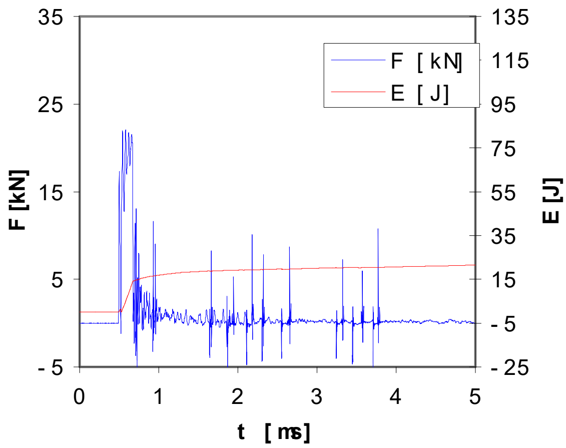

Figure 8. Specimen E1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 80s, Temp.: +20 °C, $A_{tot.}$: 22J

Graphics resulting from testing on instrumented Charpy pendulum enabled the analyses of testing results, first of all the evaluation of cooling time on the testing as well as temperature influence for total impact energy and its components, energy of crack initiation A_I and energy of crack propagation A_P.

The obtained test results show that at the same heating temperature (1350°C), the best values of the total impact energy have samples with the shortest cooling time (5s), Fig. 9. Total impact energy decreases while the cooling time increases up to 40s, and after that point stay on the same level. In other words, after $\Delta t_{8/5}$ 40s cooling time does not influence the value of total impact energy.

In most of cases nature of curves is principally identical differing only in value of maximum force P_{max}, and total impact energy A_{tot}. The total impact energy increases with increase of temperature (~14J at -20°C to ~85J at 60°C), as shown in Figs. 10 to 14. That complies with data from literature for that type of steel [4].

Table 5. Impact testing results of test samples two-pass simulated HAZ

Sample mark	Testing temp., °C	Cooling time $\Delta t_{8/5}$, s	Total impact energy, $A_{tot.}$, J	Crack initiation energy, A_I, J	Crack propagation energy, A_P J
F1	+20	10/10	88	65	23
F2			102	71	31
F3			62	42	20
G1	+20	10/10	108	71	37
G2			93	63	30
G3			88	60	27
H1	+20	10/10	57	20	37
H2			87	71	16
H3			75	55	20
I1	+20	10/20	34	20	14
I2			36	15	21
I3			36	14	22
J1	+20	10/20	18	9	9
J2			22	11	11
J3			17	9	8

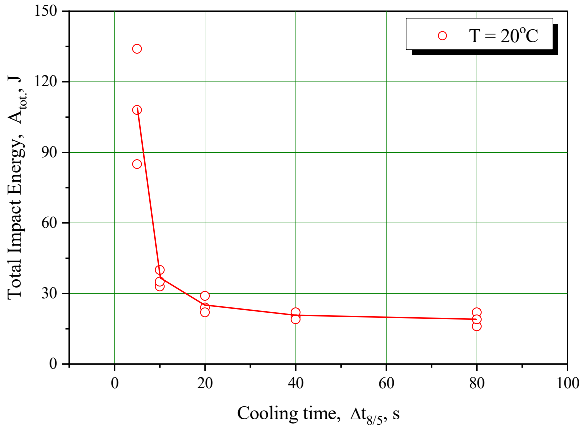

Figure 9. Diagram $A_{tot.} - \Delta t_{8/5}$ to T = 20°C

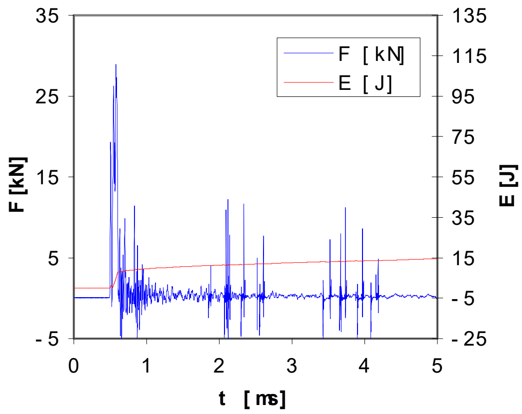

Figure 10. Specimen B1 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: -20°C, $A_{tot.}$: 14J

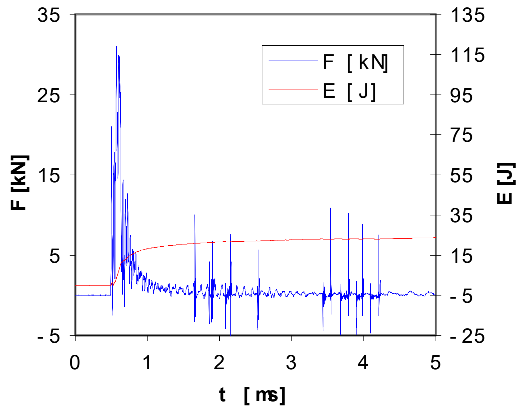

Figure 11. Specimen B4 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: 0°C, $A_{tot.}$: 24J

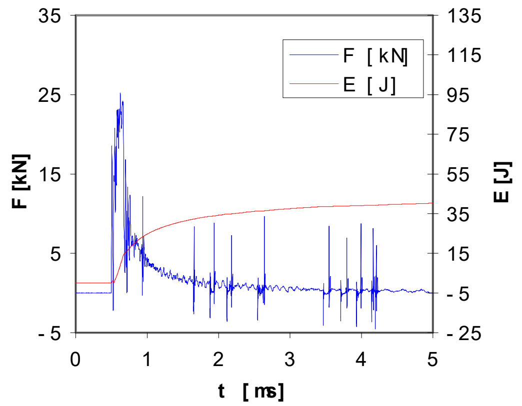

Figure 12. Specimen B7 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: +20°C, $A_{tot.}$: 40J

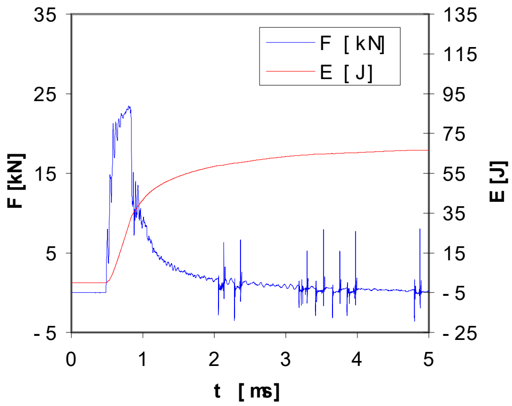

Figure 13. Specimen B10 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: 40°C, $A_{tot.}$: 67J

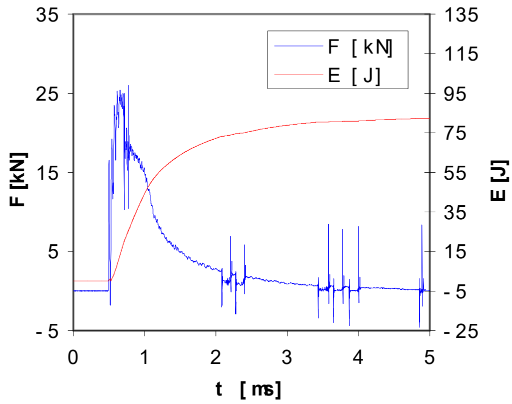

Figure 14. Specimen B13 - Simulation: T_{p1} = 1350°C, $\Delta t_{8/5}$ = 10s, Temp.: 60°C, $A_{tot.}$: 85J

Graphically, the dependence of the change in total impact energy with temperature is shown in fig. 15.

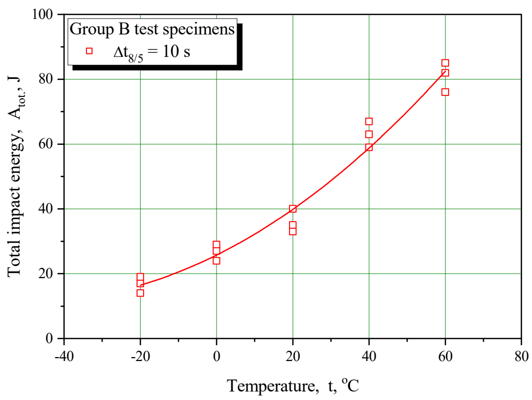

Figure 15. Diagram $A_{tot.}$ - – temp. testing at $\Delta t_{8/5}$ = 10s

The highest values of the total impact energy recorded in the two-pass HAZ, have the samples with the highest temperature of the second thermal cycle, Fig. 16. Thus, at the second thermal cycle of 1100°C and 980°C, the obtained impact energy values are on average value close to 90J, and at the second thermal cycle of 700°C, the total impact energy is around 20J [4].

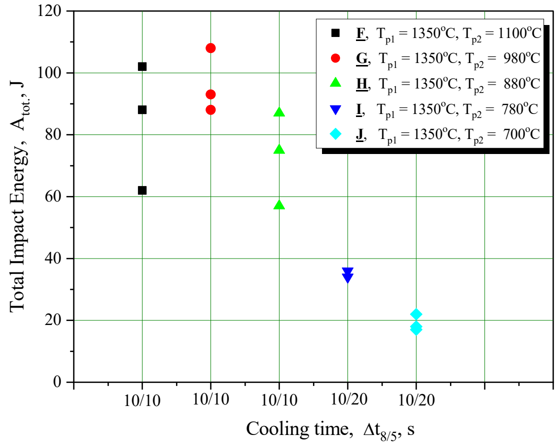

Figure 16. Diagram A_{tot} - cooling time $\Delta t_{8/5}$ at different t of the second thermal cycle

However, the interesting thing is that at -20°C the value of total impact energy decreases below impact energy of zero plasticity (transient temperature) that for HAZ NIOMOL-a 490K, in improved conditions, amounts to -27°C and at that temperature the value is 27J, based on data from literature and own research.

Decrease of participation of fracture plastic component, i.e. decrease of material plasticity is clearly reflected in the character of obtained curves, where the deflection value, D_f, decreases significantly with decrease of temperature. Dependence of deflection D_f is of the same character as dependence of total impact energy $A_{tot.}$, what means that deflection increases with increase of testing temperature.

4. CONCLUSION

The obtained results of the impact energy (impact toughness) of the simulated ZUT, microalloyed steel Niomol 490K, indicate that:

- In the case of one-pass ZUT, the best impact characteristics have samples with the shortest cooling time at the same temperature of the thermal cycle.
- In two-pass ZUT, the best impact characteristics have samples where the temperature of the second thermal cycle is the highest at the same cooling time.

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