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Effect of direct quenching on the mechanical properties of cold formed S500 rectangular hollow section

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Abstract

The aim of this work is to study the effect of cold forming on the mechanical properties and microstructure of a steel grades used in manufacturing of rectangular hollow sections. Conventional and a direct-quenched steel sections in 500 MPa strength level are compared. Tensile properties and Charpy-V impact toughness were determined for the flat side and corner of hollow section. The results show that the strength in corner area is approximately 50 MPa higher and the elongation at fracture 4 % lower compared to flat side area, revealing the work hardening and the effect of higher cold deformation rate in corner areas. The impact energies of sub-sized samples (5 mm x 10 mm x 55 mm) were at high level at -40 °C and -60 °C in both steels. However, the direct-quenched steel had improved impact toughness when testing temperature decreased. It is also notable that no differences in CV values between the flat and corner samples were observed. EBSD results showed compressed microstructure in inner corner radius and the outer was stretched in correspondingly. This resulted inner corner area having the smallest grain sizes. Additionally, a brief discussion between the mechanical properties of structural rectangular hollow sections is presented.

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Keywords: Cold forming; Direct quenching; Hardness; Charpy V-notch impact toughness; Microstructure; Rectangular hollow section; Mechanical properties; Strength;

1. Introduction

Formed steel sections are widely used in building construction due to their relatively high strength and stiffness properties. Especially, cold-formed welded hollow sections provide efficient low cost and environmentally friendly alternatives compared to hot-formed sections [1]. Cold-formed rectangular hollow sections can be manufactured from circular profiles by plastic deformation in several stages. Plastic deformation cause work hardening of the material, resulting in enhanced strength, although a corresponding loss of elongation and toughness. Nevertheless, the requirements of offshore steels are tightening as steels are used even colder conditions as previously.

Sun and Packer [2] have shown that corner impact toughness properties are lower compared to the flat side. Likewise, Guo et al. [3] have shown that corner of has the highest strength level compared to flat side, and flat side strengths are higher than raw material. Therefore, aim of this study is to compare microstructure and mechanical properties of two steels with different production routes; the conventional and direct-quenched steel. Since the recent studies [4,5] have shown that ultrahigh-strength steels with direct quenching route have enhanced toughness properties than conventionally produced steel. Especially, the purpose of this study is to report properties in the corners of hollow sections. Additional results for this paper are presented in Ref. [6]. More detailed information of the identical steels related the effect of cold forming rate (CFR)

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on the mechanical properties and microstructure can be found in the previous work of the authors [6].

2. Experimental

2.1. Materials

Microstructure and mechanical properties of two cold formed structural rectangular hollow sections (RHS) are investigated. The investigated hot rolled strip steels are produced by a conventional thermomechanical controlled processing (TMCP) and a direct quenching (DQ). Chemical composition of the steels is presented in Table 1. Tensile properties in hot rolled stage were quite similar, the yield strengths were ~450 MPa, tensile strengths 530-550 MPa and total elongations were 24-27 %. Microstructure of base materials was mainly ferritic with small fraction of carbon rich areas was found, as can be seen in Fig. 1. More detailed information of hot rolled strips can be found in Ref. [6] were cold forming rate was investigated. Wall thickness of materials was 8 mm and the section side widths were 140 x 140 mm for TMCP material and 150 x 150 mm for DQ material. External corner radius was 20 mm, which is in the middle of EN 10219 tolerance range (16-24 mm for 8 mm).

Table 1. Chemical composition of investigated steels (in wt.%).

Material	C	Mn	Nb	Ti	P	S
TMCP	0.07	1.38	0.02	0.016	0.012	0.005
DQ	0.06	0.71	0.03	0.002	0.008	0.005

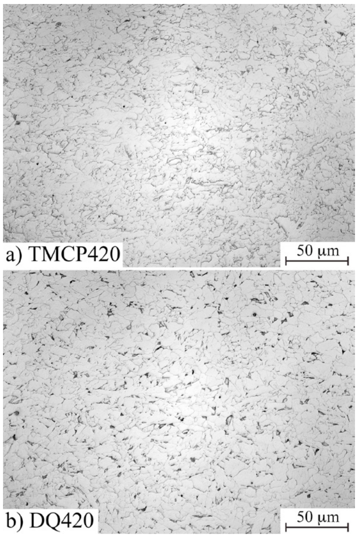

Fig. 1. Microstructure of (a) TMCP and (b) DQ base material.

2.2. Microstructural characterization

General characterization of the transformation microstructures was performed with a laser scanning confocal microscope (LSCM) after nital etched specimens. Grain boundary misorientation distribution and grain sizes were measured using an EDAX electron backscatter diffraction (EBSD) system on the Zeiss Sigma field emission scanning electron microscope (FESEM). The FESEM for the EBSD measurements was operated at 15 kV and the step size was 0.5 µm. Grain boundaries of low-angle and high-angle (effective grain size) were determined as equivalent circle diameter (ECD) values with low (>2°) and high boundary misorientation (>15°), respectively.

2.3. Mechanical testing

Samples for mechanical testing were water-cutted from both RHS materials and machined suitable for tensile and Charpy-V tests (Fig. 2).

Tensile tests were carried out using Zwick/Roell Z100 at room temperature in accordance with the standard EN ISO 6892 using flat side and two types corner specimens (wide (Fig. 2b) and narrow (Fig. 2c)) in the rolling direction. Specimen dimensions (thickness x width x parallel length) for flat side and wide corner samples were 8 mm x 12 mm x 70 mm and for narrow corner sample 8 mm x 5 mm x 50 mm, see Fig. 2.

Charpy-V notch (CVN) impact testing was performed in accordance with the standard EN ISO 148 at -40 °C, -60 °C and -80 °C temperatures (3 specimens / temperature) using longitudinal flat side and corner specimens (L-T). Impact test specimen was machined to 5 mm x 10 mm x 55 mm size.

Cross-section hardness profiles of RHS flat side and corner were measured using Struers Duramin A300 hardness tester under HV10 load in ten measurement starting and ending 100 µm below the surface. For a symmetry reason only half of the corner is presented (Fig. 3).

Fig. 2. Examples of water-cutted Charpy-V impact toughness and tensile test samples from (a) flat side and (b-c) corner of rectangular hollow section. Two types of tensile test ((b) wide and (c) narrow) specimen from corner were used.

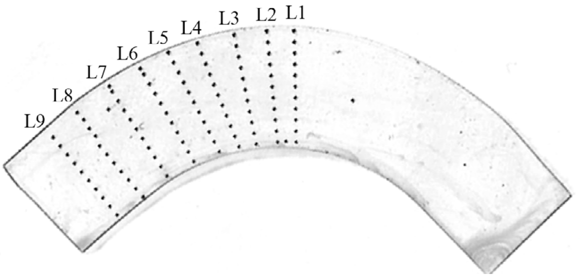

Fig. 3. Examples of hardness profiles from corner of rectangular hollow section.

3. Results and discussion

3.1. Microstructure of investigated sections

In the Table 2 are shown the EBSD measurement results for RHS materials. >2° results include both low- and high-angle grain boundaries and >15° results include only high-angle grain boundaries. Fig. 4 shown the inner (a,b), center (c,d) and outer (e,f) corner microstructures of the RHS materials. From the images can be seen that the inner microstructure is compressed, and the outer is stretched. Both steels have ferritic microstructure but DQ have much more carbon rich areas.

From the grain boundary results and Figs. 4a and b, can be seen that the inner corner areas have the smallest grain sizes where greatest compression occurs. Outer corner areas have the second smallest grain sizes and the centerline of corner areas the largest. The inner corner areas have the most low-angle grain boundaries (red color in Fig. 4) and the outer corner areas have the least low-angle grain boundaries. The low-angle grain boundary fractions are shown in Fig. 4. As noticed in the case of cold forming of strip materials in Ref. [6], where the higher cold forming increases the amount of low-angle grain boundaries, and similar effect can be seen clearly also from these RHS corner EBSD measurements. As can be seen from the EBSD grain size results, that there are no large differences in grain sizes between investigated steels.

Table 2. EBSD grain size measurements of RHS materials. Grains below 0.9 µm are clean-up from data.

	Position	TMCP	DQ
low-angle grain size	Inner corner	2.0 µm	2.0 µm
	Center corner	3.5 µm	3.6 µm
	Outer corner	3.0 µm	2.9 µm
high-angle grain size	Inner corner	3.8 µm	4.2 µm
	Center corner	4.6 µm	4.7 µm
	Outer corner	3.8 µm	4.5 µm

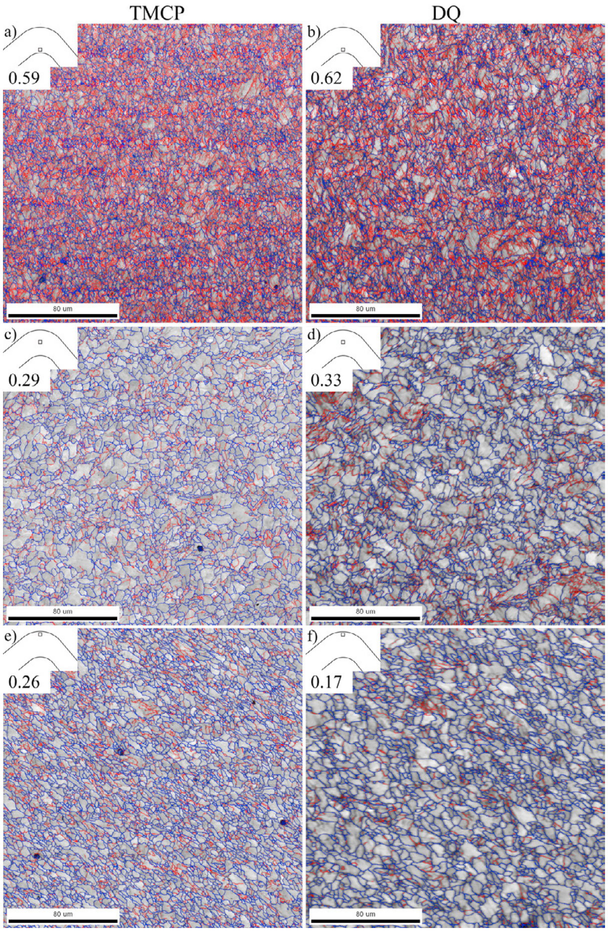

Fig. 4. EBSD image quality maps with low- (>2°, red) and high-angle (15°-62.7°, blue) boundaries. Microstructures of inner (a,b), center (c,d) and outer (e,f) corner of TMCP (left column) and DQ (right) RHS material. Low-angle grain boundary fractions are also presented.

3.2. Mechanical properties

In the Table 3 are presented the tensile test results carried from flat side, wide corner and narrow corner specimens. Generally, from the results can be seen that the strength values in corner areas are higher and the elongation values lower than in flat areas, which reveals the effect of greater cold deformation in corner areas. Strength levels in the narrow specimens are also a bit higher compared to the wide sample, which include larger cross-section of the corner area and therefore include more areas, which have undergone smaller cold deformation compared to the inside area of the corner. However, there are no notable differences in elongation values between the corner samples.

Table 3. Mean tensile test results of flat side, wide and narrow corner samples.

Material	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)	A_g (%)	$R_{p0.2}/R_m$
TMCP RHS Flat	541	571	19	2	0.95
TMCP RHS Wide	611	668	15	1	0.92
TMCP RHS Narrow	637	675	15	1	0.94
DQ RHS Flat	554	607	19	5	0.91
DQ RHS Wide	592	687	15	3	0.86
DQ RHS Narrow	666	705	16	3	0.94

Table 4 is shown individual and mean RHS CVN results of the flat side and corner samples at -40 °C, -60 °C and -80 °C testing temperatures. Fig. 5 is presenting impact energies of mean RHS corner specimens (dashed line) and cold formed specimens (round marks and solid exponential line) from previous study [6]. At -40 °C impact values are at same level, while at lower testing temperatures the direct-quenched steel has improved impact toughness as comparing the conventional TMCP steel. DQ steel has the good impact values even at -80 °C. It is also notable that there are no major differences in CVN values between the flat side and corner samples in both materials.

Comparing the mean RHS corner and cold formed strip energies, the TMCP steel is crossing in higher (cold forming rate) CFR state than DQ. For example, the at -60 °C crossing point for TMCP is approx. at 20 % CFR and for DQ approx. 8 % CRF, which might indicate that the corner of TMCP is undergo higher deformation or simply the material behavior is totally different between the direct-quenched and conventional materials.

Table 4. Charpy-V impact energies of flat side and corner samples. The sub-size (5 mm x 10 mm x 55 mm) impact test specimens were used, if using a standard sizes values would be double.

Material	-40 °C (J)			mean
TMCP RHS Flat	67	79	79	**76**
TMCP RHS Corner	77	74	78	**77**
DQ RHS Flat	89	93	92	**92**
DQ RHS Corner	94	99	92	**96**
	-60 °C			
TMCP RHS Flat	69	64	63	**66**
TMCP RHS Corner	69	52	60	**61**
DQ RHS Flat	90	103	83	**92**
DQ RHS Corner	84	94	93	**91**
	-80 °C			
TMCP RHS Flat	42	5*	42	**30**
TMCP RHS Corner	54	51	44	**50**
DQ RHS Flat	92	66	91	**84**
DQ RHS Corner	88	47	88	**75**

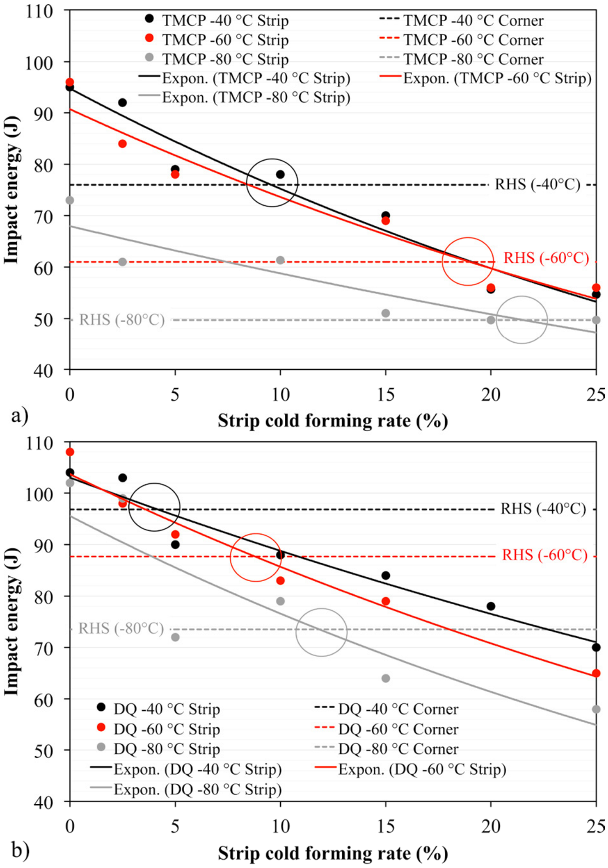

Fig. 5. Impact energies of (a) TMCP and (b) DQ steel from the corner of RHS and strip with various cold forming rates at -40 °C, -60 °C and -80 °C. Results for cold forming rate of the strip are presented in Ref. [6]. The sub-size (5 mm x 10 mm x 55 mm) impact test specimens were used, if using a standard sizes values would be double.

Additionally, defined by EN 10219, tolerance of external corner radius is 2.0 to 3.0 times wall thickness (T) for 6 to 10 mm material thickness. The theoretical plastic deformation ϵ can be calculated by the following simplified formulas [7]:

$$\varepsilon\ (\%) = \frac{T(mm)}{2R_e(mm) - T(mm)} x100\%$$

With this ideal bending equation, the maximum degree of cold forming (outer curvature elongation) is calculated as follows when external corner radius (R_e) is 20 mm: [(8/(40-8) x 100 % = 25 %]. Then the average cold forming ratio is half of that, or 12.5 %. From this it can be concluded that the TMCP RHS material has an impact energy at -40 °C on the conservative side (approx. 10 %) compared to simulated cold rolling test. It can further be concluded that, at DQ RHS corner, both -40 °C and -60 °C testing temperatures are conservative with respect to simulated cold rolling. Therefore, can be conclude, that the corner cold forming ratio can be considered as 10 % for TMCP steel at -40 °C and 10 % for DQ steel at -40 °C and -60 °C.

3.3. Hardness measurements for corner profile

Tables 5 and 6 are shown hardness measurements from corners, as illustrated in Fig. 3. Those results are summaries in Fig. 6, which are shown the RHS hardness profiles of L1-3, L4-6 and L7-9 from the inner to outer surface of corner, flat side of section and also results from effect of cold forming rates from Ref. [6]. As was seen with the strip hardness values, the RHS hardness values are increased as the strength values of the steels. From the profiles can be seen that the corners undergo significant cold forming during the continuous-forming process. Materials have the highest hardness in the inner corner areas and the softest hardness is located approximately one quarter from the outer surface. From the Fig. 6 can be seen that in the flat area near the corner (L7-9) the hardness profiles are quite flat, which tells that in the flat corner area the cold-forming level is quite same in the whole measured line. However, the inside surface of section still has slightly higher hardness level compering the outer surface. The highest hardness differences are located in the corner (L1-3) in both steels. This shows also the effect that the cold-forming level decreases when moving from the corner to the flat area of the RHS. However, those L7-9 values are much higher than real flat side values, where hardness varies between 185 to 200 HV, which corresponding less than 10 % cold forming rate.

Comparing the hardness of as-rolled condition and RHS corner (L1-3), the hardness of direct-quenched material (DQ) increased from 175 HV to 240 HV, which is more than with TMCP material. Even with higher hardness, the DQ material has better impact energies compared to TMCP.

Table 5. Hardness results of TMCP from corner of RHS.

Position	L1	L2	L3	L4	L5	L6	L7	L8	L9	**mean**
inner corner	220	217	237	232	222	236	227	227	219	**226**
	224	210	239	222	216	216	222	221	221	**221**
quarter	213	213	218	207	210	221	220	218	216	**215**
	214	214	221	208	200	216	221	217	211	**214**
middle	204	209	201	202	214	211	224	215	216	**211**
middle	195	195	206	198	218	204	218	210	217	**207**
	191	196	194	198	197	217	219	216	210	**204**
quarter	184	195	194	195	201	211	223	214	216	**204**
	191	208	197	203	209	205	220	214	221	**208**
outer corner	200	211	206	202	205	204	216	215	216	**208**
mean	**204**	**207**	**211**	**207**	**209**	**214**	**221**	**217**	**216**	**212±2**

Table 6. Hardness results of DQ from corner of RHS.

Position	L1	L2	L3	L4	L5	L6	L7	L8	L9	**mean**
inner corner	238	232	240	238	227	221	216	224	224	**229**
	249	245	230	255	231	243	232	227	225	**237**
quarter	242	233	244	249	227	229	219	237	224	**234**
	232	236	220	234	228	224	220	218	230	**227**
middle	229	227	217	221	212	210	213	224	219	**219**
middle	209	208	205	205	204	204	208	215	229	**210**
	200	193	196	201	209	202	201	212	223	**204**
quarter	193	204	198	202	205	202	202	213	219	**204**
	199	211	213	208	202	205	205	206	227	**208**
outer corner	219	219	223	214	213	215	213	203	-	**215**
mean	**221**	**221**	**219**	**223**	**216**	**216**	**213**	**218**	**224**	**219±3**

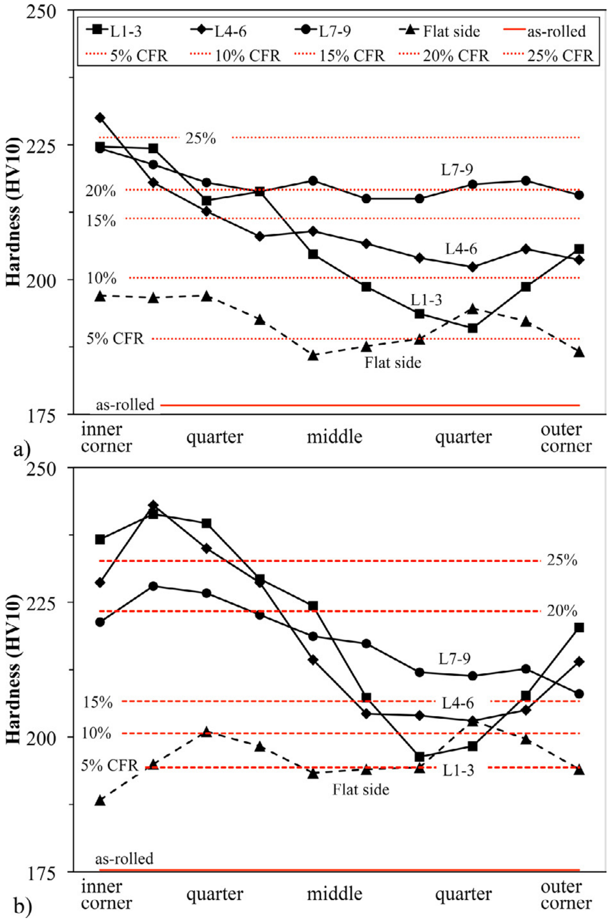

Fig. 6. Three different hardness profiles (L1-3, L4-6 and L7-9) from corner to flat area and mean hardness of as-rolled and different cold forming rates (CFR) for (a) TMCP and (b) DQ material.

3.4. Relationship between the microstructure and mechanical properties

As the EBSD grain sizes or microstructural features does not show differences between the investigated steels, thus correlations between the hardness and tensile strength and impact toughness are presented in Figs. 7-9 to find explanations for better impact toughness of DQ material.

Fig. 7 shows correlation between the hardness and tensile strength. Those results are from CFR study [6] and the mean flat side and corner hardness values. The mean hardness and 95 % confidence limits of the mean from the corner measurements was 212 ± 2 HV and 219 ± 3HV for TMCP and DQ materials, respectively. Hardness and tensile strength are increasing as the cold forming rate increases, which is typical for steels. However, from Fig. 7 can be seen that RHS (flat side, wide and narrow corner) values are not fit as good as cold formed strip results. Conventional TMCP corner values are lower than cold formed strip and higher with direct-quenched DQ material, which means that direct-quenched steel tensile strength increases more than hardness during the cold forming the RHS.

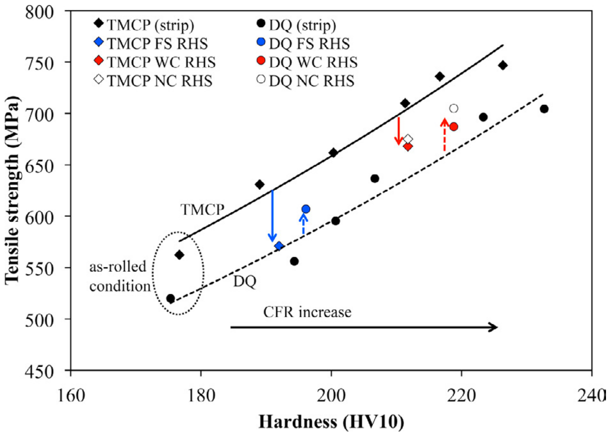

Fig. 7. The correlation between hardness and tensile strength of strip steel with 0 – 25 % CFR (black), flat side (FS, blue), wide corner (WC, red) and narrow (NC, white) specimen.

Similar behavior can be seen in Fig. 8, where flat side impact energies of the TMCP steel at -40 °C are lower than expected. Conversely, DQ steel has higher impact energies as the strength level assume. Nevertheless, presented results are consistent with Guo et al. [3], which have shown that corner of has the higher strength level compared to flat side, and flat side strengths are higher than as-rolled material.

Sun and Packer [2] have state that corner impact toughness properties are lower compared to the flat side. However, similar cannot be seen clearly from current results (Table 4 and Fig. 8), since impact energies between flat side and corner are rather comparable.

Fig. 9 is presenting relationship between the hardness and impact energies at -40 °C, -60 °C and -80 °C testing temperature for cold formed and corners materials (TMCP solid and DQ dashed). Those results are showing that direct-quenched material hardening at the corner more than conventional (TMCP) steel, and still the impact energies are much better in DQ material RHS corner. In generally, the impact energies are better in direct-quenched DQ steel than conventional TMCP steel.

Several studies [8–10] has shown that coarse TiN inclusions can decrease the toughness properties, however microstructural characterization do not show any coarse TiN in TMCP material even it has higher titanium content compared to DQ material. Nevertheless, in the future appropriate inclusion analysis and fractographic examination for the Charpy V-notch samples should be done, to clarify the reasons for better impact energies in direct-quenched state.

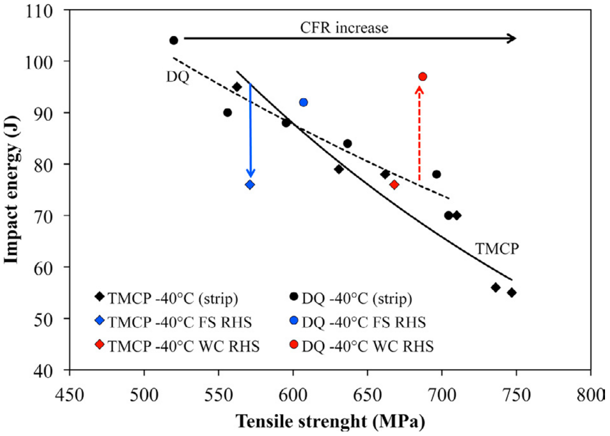

Fig. 8. The correlation between tensile strength and impact energy of strip steel with 0 – 25 % CFR (black), flat side (FS, blue) and wide corner (WC, red) specimens. The sub-size (5 mm x 10 mm x 55 mm) impact test specimens were used, if using a standard sizes values would be double.

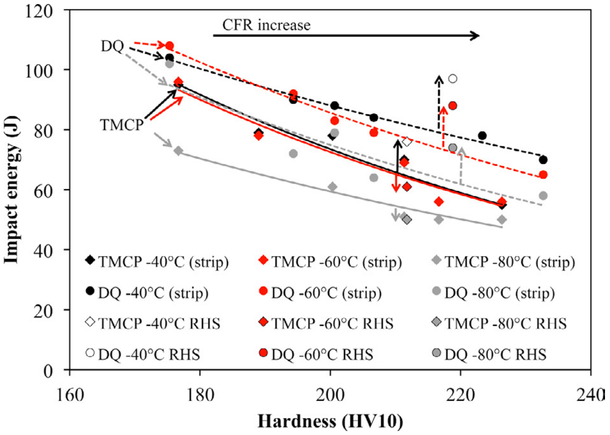

Fig. 9. The relationship between hardness and impact energies of strip steel with 0 – 25 % CFR and corner specimen at -40 °C (black), -60 °C (red) and -80 °C (grey). The sub-size (5 mm x 10 mm x 55 mm) impact test specimens were used, if using a standard sizes values would be double.

4. Summary

Mechanical properties and microstructure of conventional TMCP and a direct-quenched cold-formed rectangular hollow section (RHS) were studied. Microstructural characterization showed that inner curvature of hollow section corners were compressed, and the outer were stretched. This resulted that the inner corner areas had the smallest grain sizes. And higher cold forming rate at the increased the amount of low-angle grain boundaries. RHS hardness profiles showed that the corners undergo significant cold-forming during the continuous-forming process. All materials had the highest hardness in the inner corner and the softest hardness was located approximately one quarter from the outer surface. In the flat area near the corner the hardness profiles were quite flat, which is a sign that in the flat area the cold-forming level is quite same in the whole cross-sectional area. The impact energy values were very high level at -40 °C and -60 °C in both RHS, even the most cold-formed areas, however the direct-quenched steel had much better impact toughness when testing temperature decreased. It is also notable that there were no differences in CV values between the flat and corner samples. The strength values in corner areas were higher and the elongation values lower than in flat areas, which reveals the effect of greater cold deformation in corner areas. The corner cold forming ratio can be considered as 10 %.

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