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Effect of Cutting Gases on the Hardness of Thermally Cut High Strenght Steels

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Abstract

In this work, it was illustrating the consequences of flame cutting on XAR® 400 and S960Q type high-strength steels. During flame cutting, the metal, locally heated to ignition temperature, burns in the oxygen beam and removes the resulting combustion product from the kerf. As a result of the process, chemical and physical changes occur in the microstructure of the steel, which can have a significant effect on its properties. Examining the microstructural transformations due to flame cutting of high-strength steels is essential from the point of view of proper design and production. In case of XAR® 400 steel quality, increasing the cutting oxygen significantly changes the microstructure, with a high reduction in hardness in the heat affected zone at cutting zone. For S960Q steel, flame cutting does not cause a drastic change in the microstructure of steel, and increasing the amount of cutting oxygen does not significantly change the hardness.

Keywords: *flame cutting, hardening, high strength steel.*

1. Introduction

Nowadays, high-strength and high strength steels are becoming increasingly popular [1, 2]. The main driving force is the need to reduce the mass of the structure. After all, from the material with higher mechanical properties, a smaller section cross section or wall thickness is enough to bear the same load. Since the density of structural and increased strength steels is almost identical, it can be seen that the weight of structures and vehicles built in this way will be less with the same strength [3, 4].

When manufacturing structures, these steels have to be cut and sometimes welded. The cold working methods, shearing and punching, can be used up to a plate thickness of about 10 mm and are mainly limited to the softer structural steels [5]. High strength steels can typically be processed by thermal cutting, but especially in thick plates, a number of microstructural changes can occur. Sometimes cracking at the cut edges [5].

XAR 400 steel, produced by Thyssan Krupp Steel, is characterised in particular by high wear resistance and good impact strength, as well as good bending and welding properties. Plates of the XAR® 400 grade receive the required properties as a result of austenitizing and follow-on quenching in special facilities and where applicable, tempering below Ar1. Its main applications are in maintenance, metallurgy, energy industry, coal and cement production [6].

SSAB's tempered high-strength steel S960QL owes its high strength characteristics to its alloying content and heat treatment (two-cycle) consisting of hot rolling hardening (Q) and high temperature tempering (HTT).

In the case of thermal cutting of high strength steels, as in welding, changes in the microstructure occur. It is known from the literature that when high strength steels are welded, the microstructure and consequently the hardness in the heat affected zone changes [7, 8]. High strength steels show a higher sensitivity to welding and cutting heat input compared to conventional structural steels. While in low or medium strength steels the HAZ toughness and hardness can be significantly affected by the t8/5 cooling time, in S960QL significant hardening and toughness reduction was observed in the whole cooling time range of the most common arc welding processes $t_{8/5} = 2.5–30$ s. In case of $t_{8/5}$ = 100 s softening and extremely low Charpy V-notch impact test values were identified [9].

The question arises: what happens in the area around the cut edge when cutting thick plates? How will the cutting technology affect the vicinity of the cut edge?

2. Materials and Testing

For the experiments, micro alloyed and fine-grained high-strength steels of type XAR®400 and S960Q were flame cut. The nominal composition of XAR®400 steel is: C = 0.14 %, Si = 0.22 %, Mn = 1.14 %, Al = 0.1 %, B = 0.002 %, P = 0.01 %, S = 0.001 %, Cr = 0.23 % Mo = 0.01 %, Nb = 0.02 %, Ti = 0.05 % [10].

The nominal composition of S960Q steel is: C = 0.16 %, Si = 0.2 %, Mn = 1.22 %, Cr = 0.2 %, Ni = 0.05 %, P = 0.011 %, S = 0.01 % [11].

Different thicknesses of steel plates were used in the tests. The measurements were carried out on steel plates with a thickness of 8 mm for XAR®400 and 10 mm for S960 Q. Microstructure of the studied steels is shown in Figure 1.

For our experiments, 300 mm long test pieces were cut at Linde Hungary Zrt.'s Budapest site for both high strength steels.

The technological data are shown in Table 1.

In case of the manual cutting gun there was an oxygen feed, in the machine cutting gun there was a separate heater and cutter oxygen feed, the burner design was head-mixed.

In the case of the flame cutting process, the flame heats the material at the surface until its ignition temperature is reached. In addition, oxygen is blown into the kerf. At this point the material starts to burn, and the cutting process begins. Thereafter, the combustion releases further heat. This in turn heats the underlying material up to ignition temperature. This allows the process to continue automatically into the depths. The metal oxides are blown out of the kerf together with the cutting oxygen.

The used cutting gases physical properties differ between them. The flame temperature in case of acetylene can achieve ≈3200° C in oxygen and ≈2100 °C in air (see Table 2). Such a high temperature makes faster piercing and cutting possible.

At the same time, acetylene's secondary flame temperature is comparatively low. Propane can reach quite high temperatures. The maximum is around 2800 °C. Compared to acetylene, the concentration of the flame is smaller, resulting in a larger HAZ and longer piercing time. The cutting speed is comparable, though. The ratio of oxygen to propane is around 4.3:1. Thus, reaching the maximum temperature requires around 3.5 times more oxygen than oxy-acetylene cutting [12].

2.1. Preparation of specimens

After the cutting process, for each flame cut the changes in microstructure at the beginning of the cuts was investigated, in the middle of the cuts and at the end of the cut edge vicinities. For metallo-

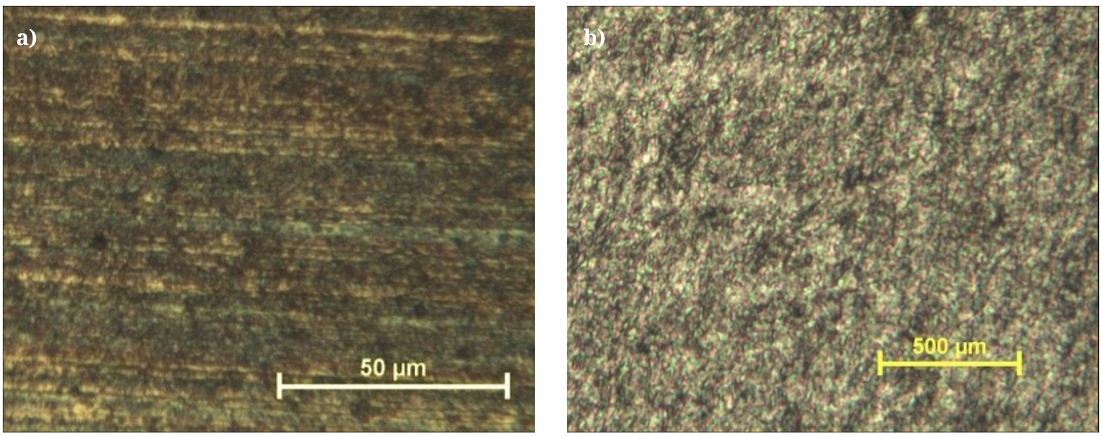

Fig. 1. *The microstructure of the tested steel plates a) XAR®400 b) Q960.*

Table 1. *Sample notification and technological data*

Sam-ple	Nozzle	burner/ fuel	$p_{O2\ Heat}$	$p_{O2\ cut}$	p_{CH}	$V_{O2\ Heat}$	$V_{O2\ cut}$	V_{CH}	v	l	kerf
			bar			L/h			cm/min	mm	
CAK	ANME10-30	C_2H_2	4	4	0,5	700	1500	350	48	10	
CPK	HP337	C_3H_8/O_2	3	4	0,5	600	1450	200	33	11	1.6
CAG	ANME10-30	C_2H_2	2	4	0,5	400	2400	350	58	8	
CPG	PNME10-25	C_3H_8/O_2	2	3	0,5	400	1200	200	36	10	1.7
DAG	ANME10-30	C_2H_2	2	4	0,5	400	2400	350	46	8	
DPG	PNME10-25	C_3H_8/O_2	2	3	0,5	400	1200	200	34	10	1.7

Markings used:
- first character: material quality (C- XAR®400/8; D – S960 Q/10),
- second character: gas (A: acetylene, P: propane),
- third character: G: „mechanical” (separate heating and cutting oxygen feed, mixing torch design), K: manual (one O_2 feed),

Nozzle – nozzle factory mark, for traceability,
- burner/fuel – gas combination used for the preheating flame,
- $p_{O2\ Heat}$ (bar) – pressure of oxygen gas used for preheating flame,
- $p_{O2\ Cut}$ (bar) – cutting oxygen pressure,
- p_{CH} (bar) – pressure of combustible gas,
- $V_{O2\ Heat}$ (l/h) is the amount of oxygen used for the preheating flame,
- $V_{O2\ Cut}$ (l/h) is the amount of oxygen used for cutting,
- V_{CH} (l/h) is the quantity of combustible gas,
- v (cm/min) is the cutting speed,
- l (mm) is the distance between the burner and the workpiece,
- kerf (mm) size of cut gap.

Table 2. *Main physical properties of fuel gases*

Characteristics	Propane	Acetylene
	C_3H_8	C_2H_2
Density at 15 °C, 0.1 MPa, (kg/m³)	1.87	1.171
Density in comparison to air (air=1)	1.55	0.9
Ignition point in air, (°C)	466	335
Ignition limit, (V%)		
In air	2.1–9.5	3–82
In oxygen	2.0–48	3–93
Flame power, (W/mm²)	104.5	448
Flame temperature, (°C)		
In air	1920	2100
In oxygen	2780	3126
Heating rate, (kJ/m³)	92000	56800

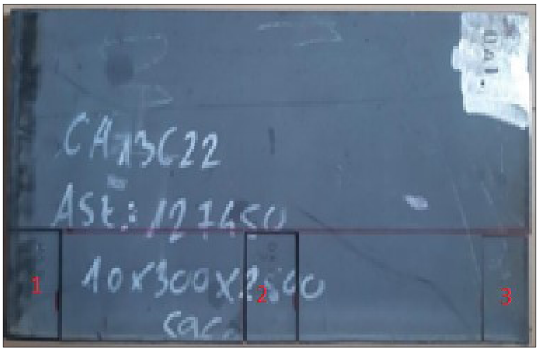

Fig. 2. *Cutting arrangement of samples: „1” specimen - start of cutting, „2” sample - middle of cutting, „3” sample - end of cutting*

graphic study the sample were cut by the waterjet cutting technique at Woldem Ltd. The cutting design is illustrated in **Figure 2**: the first sample was cut at the beginning of the plate, then in the middle and at the end. The use of waterjet cutting was also necessary to avoid heat exposure to the pieces during cutting.

After water jet cutting, samples cut from the same sheet were simultaneously cold-embedded using two-component Duracryl plus acrylic resin. After solidification of the acrylic resin, the samples were prepared using increasingly finer grinding paper (P60, P 100, P 220, P 400, P 600, P 1200) and polished with 3 µm and 1 µm diamond paste at Buehler Ecomet 250 Pro equipment. The microstructure changes were studied after etching with Nital-e etchant.

The hardness distribution of the samples was determined with Buhler Wilson W 3111S by HV 5 hardness measurement. The indentation distance in the immediate vicinity of the cutting edge and in the heat affected zone was 1 mm and outside of the heat affected zone was 5 mm.

For the examination and evaluation of the hardness indentation, Zeiss Axio Observer Z1m optical microscope and the associated computer software were used.

3.Results

It was investigated if there is a difference between manual cutting and mechanical cutting. In our experiments, the effect of the quality of the burner gases (acetylene or propane) was studied, while their pressure was kept at the same value.

3.1. Microstructural changes in case of flame cutting of XAR®400 steel plates

In case of XAR®400 steel plate cutting, it was found that microstructure changes occur near the cutting edge in each case, when various fuel gases were applied. About 100 µm thick decarburized layer was observed near the cut edge, as it is visible at Figure 3.

For XAR400 steel, hardness measurements near the cut edge show that the effects of propane and acetylene were similar at the beginning (Figure 4), middle (Figure 5), and end (Figure 6), of the cut edge when applied by hand torch, but differed when the machine torch was operated (Figure 7).

Towards to the end of the cutting zone, softened thickness exceeds 5 mm (the hardness is less than 300HV5). When cutting were effectuated with propane, this material softened layer thickness was lower than when acetylene was applied in case of manual cutting work (Figure 6).

Studying the Figures 4., 5. and 6. it can be concluded that the hardness values in the immediate vicinity of the cutting edge are more favourable using propane fuel gas, although the differences cannot be said to be drastic. Away from the cutting edge, the hardness sets to almost the same value. The different hardness values near the cutting edge may be explained by the flame power differences. Acetylene has a much higher flame power (448 W/mm^2) than propane (104.5 W/mm^2), so grain coarsening appearance is more likely near the cutting edge, resulting in deterioration of hardness values.

When using a machine torch, acetylene caused more pronounced softening on the cutting edge of the plate at the outer 5mm than propane, and the softened zone is clearly wider than when using a manual torch (Figure 7.).

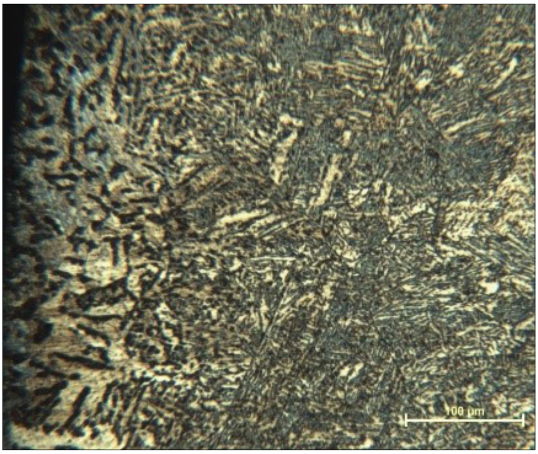

Fig. 3. *Microstructural change in the cutting vicinity in the case of XAR 400 steel plate.*

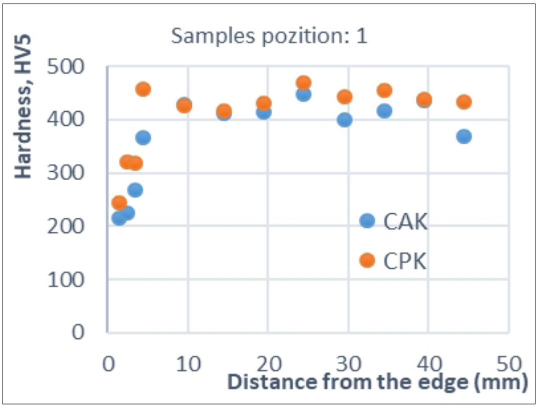

Fig. 4. *Hardness variation from the cutting edge for CAK/CPK pieces at the beginning of the cutting. Manual torch.*

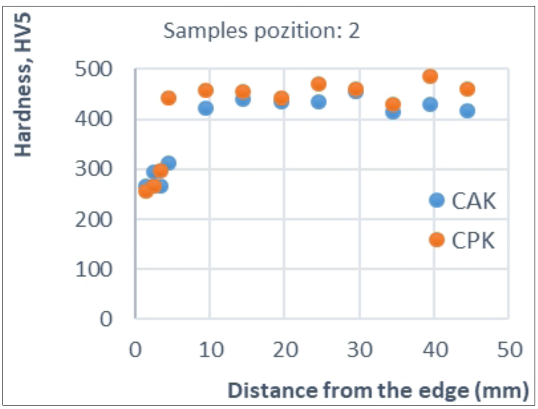

Fig. 5. *Hardness variation from the cutting edge to the inside of the sample for CAK/CPK pieces at the middle of the cutting. Manual torch.*

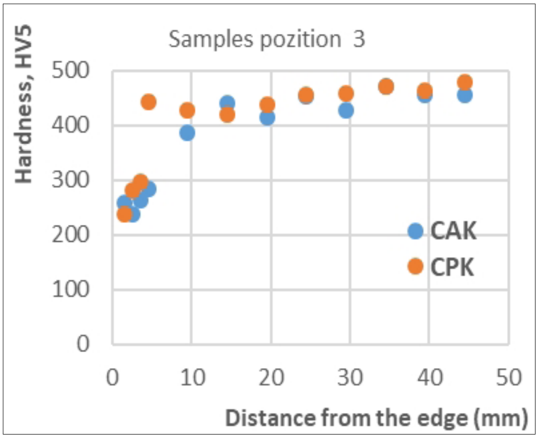

Fig. 6. *Hardness variation from the cutting edge to the inside of the sample for CAK/CPK pieces at the end of the cutting. Manual torch.*

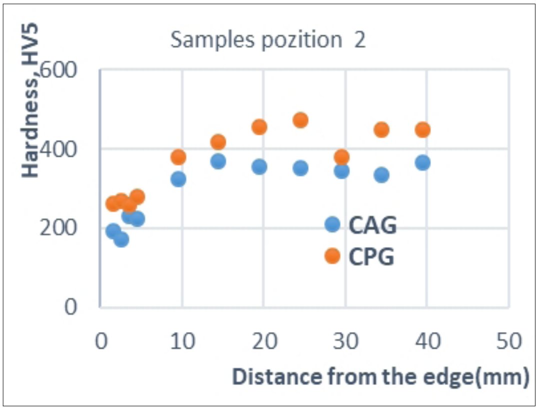

Fig. 7. *Hardness variation from the cutting edge to the inside of the sample for mechanically cut CAG/CPG pieces at the middle of the cutting.*

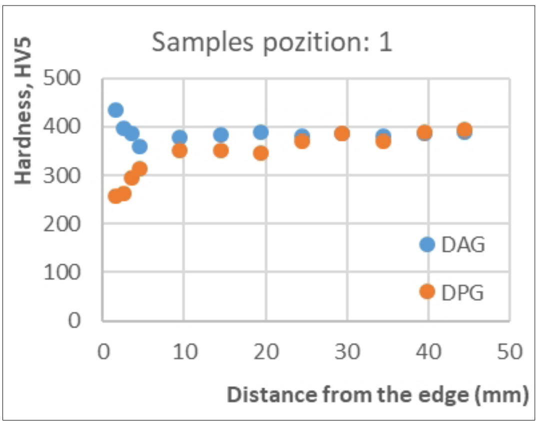

Fig. 8. *Hardness variation from the cutting edge to the inside of the sample for mechanically cut S960Q steel plate (DAG/DPG pieces).*

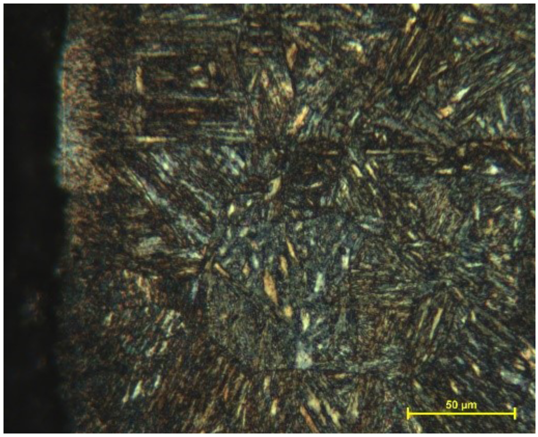

Fig. 9. *Microstructure of 960Q steel plate near the cutting edge.*

3.2. Effects of different fuel gases on the microstructure of S960Q steel plate during cutting

The effects of propane and acetylene differ significantly for 960Q steel grades. While acetylene caused an increase in hardness at the outer 5 mm of the cut edge, propane caused a softening of this zone, as shown in **Figure 8**. Moving away from the cutting edge, the hardness values of the two samples are almost identical.

Examining the microstructure of the steel, a 10 µm thick layer of melted and re-solidified material was observed in the vicinity of the cut edge. Within it, bainite formed from coarse-grained primary austenite can be seen (**Figure 9**). Right next to the cutting edge, it can be observed that the material has been melted. As a result of melting, the formation of some dendritic tissue can be seen at a large ki thickness.

4. Conclusion

Based on the results and experience summarised in the article, the following main conclusions can be made:

1. XAR400 steel grade is not recommended to be cut by flame cutting process. The microstructure can be transformed at great depths under the influence of the flame, thereby also reducing the hardness values.
2. For XAR400 steel grade, increasing cutting oxygen caused a decarburization in microstructure and the greatest decrease in hardness.
3. Basing on the results the S960Q steel grade can be properly cut by flame cutting process. The cut does not cause drastic changes in micro-

structure. The sample recrystallizes, but the recrystallized zone is small enough to be reprocessed or removed by a slight post-processing during post-cut welding.

4. With regard to S960Q steel grade, no change in cutting oxygen quantity can be observed being significant in terms of hardness as in the XAR400 steel grade.

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