Broj rada: 5.9
DOI: 10.65156/wws.sjdp.si.031

STRUKTURNE TRANSFORMACIJE ČELIKA IZAZVANE PRIMJENOM PLINSKOG REZANJA UZ UPORABU ACETILENA I SMJESE PROPANA/BUTANA

STRUCTURAL TRANSFORMATIONS OF STEEL INDUCED BY APPLICATION OF OXYFUEL GAS CUTTING USING ACETYLENE AND PROPANE/BUTANE MIXTURE

Prof. Zoran Kožuh, PhD, ORCID: 0000-0003-2818-174X; Prof. Zdravko Schauperl, PhD, ORCID: 0000-0001-7388-8555; Jadranka Eržišnik, Dipl. Ing.

1 University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10000 Zagreb, Croatia

E-mail: zoran.kozuh@fsb.hr

Rezime: U metaloprerađivačkoj industriji plinsko rezanje široko je rasprostranjen i uobičajen postupak rezanja čelika. Taj je postupak obično prva operacija u pripremi materijala, a cilj mu je dobivanje rezne površine spremne za sljedeću operaciju, najčešće zavarivanje. Eksperimentalni dio ovog istraživanja bavi se utjecajem plinskog rezanja uz uporabu acetilena i smjese propan-butana na mikrostrukturu i tvrdoću niskolegiranog visokočvrstog čelika S960 QL. Utvrđene su značajne razlike u mikrostrukturi i tvrdoći reznih površina te u veličini zone utjecaja topline između površina dobivenih rezanjem acetilenom i onih dobivenih plinskim rezanjem uz uporabu smjese propan-butana. Uz rubove rezne površine utvrđena je i dekarbonizacija, neovisno o vrsti plina korištenog pri rezanju i neovisno o tome je li provedeno predgrijavanje.

Ključne riječi: plinsko rezanje, acetilen, propan-butan, mikrostrukturne promjene

Abstract: In metal processing industry oxyfuel gas cutting is a widespread and common procedure for cutting steel. This procedure is usually the first operation in material preparation whose objective is producing cutting surface ready for the next operation, usually welding. Experimental part of this study deals with influence of oxyfuel gas cutting with use of acetylene and propane-butane mixture on microstructure and hardness of low-alloyed high-strength steel S960 QL. Significant differences in microstructure and hardness of cutting surfaces as well as heat affected zone size have been determined for surfaces created by cutting with acetylene and those created by oxyfuel gas cutting with use of propane-butane mixture. Decarburization along the edges of cutting surface has also been established regardless of type of gas used during cutting or of the fact that preheating was conducted.

Keywords: oxyfuel gas cutting, acetylene, propane-butane, microstructural changes

1. INTRODUCTION

Oxyfuel gas cutting is widely used for steel preparation because it provides a rapid and economical method for cutting a broad range of plate thicknesses. In fabrication practice it is often the first operation before welding, so the metallurgical condition of the cut edge can directly affect subsequent processing. High-strength steels therefore require particular attention to heat input, cooling rate and the resulting heat-affected zone.
Acetylene and propane-butane mixtures are among the most commonly used fuel gases. The cuttability of steel depends primarily on chemical composition and on the thermal conditions during cutting. Low-carbon and low-alloy steels generally show good cuttability, whereas increasing carbon and alloying-element contents increase the tendency to hardening and cracking.

The effect of chemical composition on the potential hardness increase in the cutting zone can be estimated using the carbon-equivalent expression (1) [1]:

$$C_{ekv} = C + 0.16\,Mn + 0.3\,Si\,(Si+Mn) + 0.4\,Cr + 0.2\,V + 0.04\,(Ni + Cu) \quad (1)$$

1.1 Metallurgical effects of oxyfuel gas cutting

During oxyfuel gas cutting, the exothermic reaction and the preheating flame rapidly raise the temperature of the material adjacent to the cut. As the heat source moves away, the surrounding colder material promotes rapid cooling. The resulting thermal cycle is comparable to that in other thermal cutting and welding processes and can produce local phase transformations, grain growth and changes in hardness in the heat-affected zone.

The extent of microstructural change depends on the heat introduced per unit volume, cutting speed, oxygen conditions, plate thickness and steel composition. Material heated above the austenitization temperature may transform during cooling and become harder near the cut edge. The hardness then generally decreases with distance from the cut as the peak temperature of the thermal cycle decreases [2].

If a hardened layer is unacceptable for subsequent processing, it can be removed by machining. High hardness and coarse austenitic grain size can increase cracking susceptibility, particularly in thicker or more highly alloyed steels. Preheating lowers the cooling rate and can therefore reduce the maximum hardness and cracking tendency [2].

1.2 Changes in chemical composition near the cut edge

Chemical-composition changes may also occur in a narrow region adjacent to the cutting surface. Literature reports both carburized and decarburized areas, which have been related to carbon redistribution, selective oxidation and interaction with molten material and slag. The magnitude and direction of these changes depend on the local thermal and chemical conditions during cutting [2,3].

1.3 Previous studies

Muñoz-Escalona et al. compared acetylene and propane during oxyfuel cutting of AISI 1045 steel and reported differences in cut quality, hardness and microstructure depending on fuel gas and cutting speed. Higher hardness near the cut edge was observed with acetylene under some conditions, while microstructural changes diminished with increasing distance from the cutting surface [4].

Ito et al. investigated oxy-acetylene cutting of high-strength low-alloy steels and showed that preheating can reduce heat-affected-zone hardness and cracking susceptibility. Their results also indicated that cutting speed, post-heating conditions and removal of the affected layer influence the behavior of cut edges during subsequent welding [5].
These findings indicate that both the thermal cycle and local chemical changes at the cut edge must be considered when oxyfuel cutting is applied to high-strength steels, which provided the basis for the present comparison of acetylene and propane-butane cutting of S960 QL steel.

2. EXPERIMENT

Influence of gas type (acetylene or propane-butane mixture) and preheating temperature on microstructure and hardness of low-alloy high-strength steel S960 QL was investigated in the experimental part of this study. Low-alloy high-strength steel S960 QL is mostly used when high strength and minimum mass of product is needed. This is often the case for different parts of technical vehicles and cranes. Four cuts were made with and without preheating, two with use of acetylene and other two with use of propane-butane mixture.

2.1 Preparation of work pieces

Oxyfuel gas cutting was conducted on metal sheets made from low-alloy high-strength steel S960 QL with dimensions of 150x150 mm and 22 mm thick. Table 1 shows chemical composition of steel S960 QL, and Table 2 gives its mechanical properties.

Table 1 - Steel S960 QL chemical composition

Element	C	Si	Mn	P	S	Al	Cu
Content, %	0.173	0.297	0.87	0.013	0.0007	0.075	0.05
Element	Mo	Ni	Cr	V	Nb	Ti	B
Content, %	0.506	0.979	0.474	0.043	0.011	0.002	0.0015

Table 2 - Mechanical properties of steel S960 QL

Material	Tensile strength Rm, N/mm2	Yield strength Re, N/mm2	Elongation A5, %	Vickers Hardness HV10
S960 QL	1069	1006	14.1	~310

2.2 Oxyfuel gas cutting system using acetylene and propane-butane mixture

Figure 1 shows Optotaj 15/20 oxyfuel gas cutting system, oxygen, acetylene and propane-butane regulators and system console.



Figure 1 - Oxyfuel gas cutting system for cutting with use of acetylene and propane-butane mixture, Welding Laboratory, FSB Zagreb

2.3 Oxyfuel gas cutting procedure

Oxyfuel gas cutting with use of acetylene or propane-butane mixture was conducted according to oxyfuel gas cutting system instructions and other available data for this type of

material. Optimal cutting parameters were used. Table 3 gives parameters used during oxyfuel gas cutting.

Table 3 - Parameters used during automatic oxyfuel gas cutting

Gas	Cutting speed [mm/min]	Pressure [bar]			Distance of inner flame cone from metal sheet [mm]	Brand and type of nozzle
		Combustible gas	Oxygen for preheating	Oxygen for cutting		
Acetylene	400	0.5	2.5	5.0	8.0	Ž-RAM-82 Tip B
Propane-butane mixture	460	0.7	2.5	7.0	8.0	HARRIS 01/2-VVC

Figure 2 shows nozzle used for cutting.



Figure 2 - Nozzle for oxyfuel gas cutting with acetylene (right, Ž-RAM-82 Tip B) and nozzles for cutting with propane-butane mixture (left, HARRIS 01/2-VVC)

Before conducting experimental cutting both metal sheets were cut in half using gas cutting with acetylene without preheating. Four sheets with dimensions 150x250 mm (AC1, PB1, AC2, PB2) were obtained for testing purposes.

Preheating temperature calculation according to Ito-Bessy's expression (2,3):

$$T_{0min} = 1440 \cdot P_w - 392\ [°C] \tag{2}$$

$$P_v = P_{cm} + d/600 + H/60 \tag{3}$$

where P_{cm} is given in expression (4), H is diffusion hydrogen content and d is sheet thickness in this case d = 22 mm.

During welding H should not exceed 5 ml/100 g of weld due to possibility of hydrogen blistering.

$$P_{cm} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B \tag{4}$$

In first calculation of preheating temperature $H = 5$ was taken. According to catalogue of material Dillimax 965 equivalent to material S960 QL $P_{cm} = 0.30$ while calculated value for sheet of this composition is $P_{cm} = 0.3145$. [6]

Preheating temperature for $H = 5$ should be $T_{0min} = 234$ °C but according to manufacturer recommendations preheating temperature for oxyfuel gas cutting should not exceed 180 °C. For $H = 3$ calculated value of temperature is $T_{0min} = 186$ °C.

Temperature of 180 °C was chosen as reference value due to following reasons:

according to the material manufacturer recommendations maximum preheating temperature should not exceed 180 °C. This temperature gives good insight in microstructural changes as a result of cutting with or without preheating.

Specimen cutting was conducted according to cutting plan shown in Figure 3. with parameters given in Table 3, as follows:

1. Cutting of sheet AC1 without preheating
   - Oxyfuel gas cutting with acetylene and oxygen mixture
2. Cutting of sheet AC2 with preheating
   - Oxyfuel gas cutting with acetylene and oxygen mixture
3. Cutting of sheet PB1 without preheating
   - Oxyfuel gas cutting with propane-butane and oxygen mixture
4. Cutting of sheet PB2 with preheating
   - Oxyfuel gas cutting with propane-butane and oxygen mixture

Temperature on the sheet surface (sheet AC2) at the cutting line was 240 °C and on the edge of the sheet was 170 °C in the last preheating pass for cutting with acetylene. Furthermore, while preheating for cutting with propane-butane mixture (sheet PB2) temperature on the sheet surface at cutting line was 240 °C and 150 °C on the edge of the sheet.

2.4 Specimen preparation

Specimens for testing were taken from metal sheets on which oxyfuel gas cutting was conducted as shown on Figure 3. Specimens were water jet cut at company DOK-ING d.o.o. Taken specimens were 12 mm wide and were taken from layer 11 mm away from the cutting surface. Water jet cutting was used for extracting specimens due to need for minimum heat input. In order to get parallel surfaces necessary for analysis specimens were additionally grinded in Laboratory for machine tools at Faculty of mechanical engineering and naval architecture in Zagreb. Grinding was chosen because of expected hardness for this low-alloy high-strength steel (S960 QL) of 450 HV10 at cutting surface and 300 HV10 for interior layers [6].

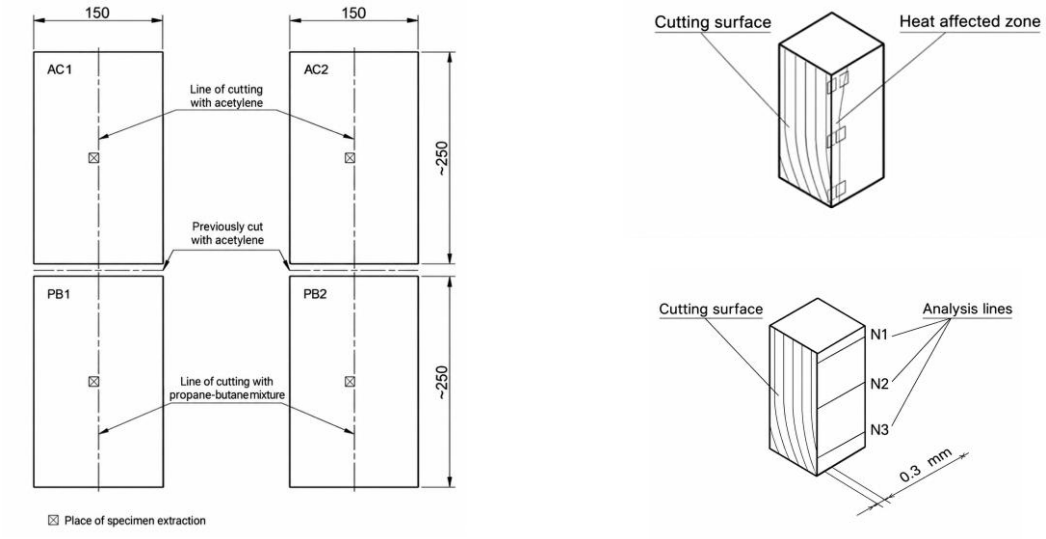


Figure 3 - Metal sheets and line of cutting (left), specimen preparation and analysis lines (right)

2.5 Microstructure analysis

Microstructure analysis was conducted in Metallographic laboratory at Faculty of mechanical engineering and naval architecture in Zagreb. Analysis included preparation of metallographic specimen, microstructure analysis and microhardness testing according to Vickers HV0.2. Every specimen was first sealed in DUROFIX 2-kit two component acrylic mixture. After sealing, specimens were grinded and polished according to recommendations for that type of material.

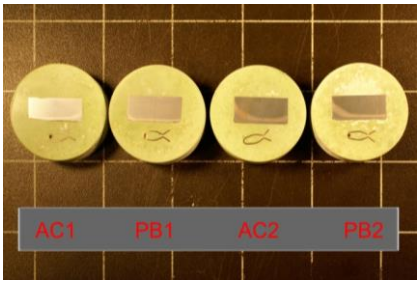


Figure 4 - Specimens prepared for analysis

Metallographic analysis with use of Olympus GX51 light microscope was conducted after metallographic specimen preparation. All four specimens were observed at magnification of 500:1 on three areas along cutting edge with equal spacing: along upper sheet side, in the middle and along bottom side. Furthermore, each specimen was analyzed in all three areas along line of microstructural changes at same magnification. Figure 5 shows base material microstructure.

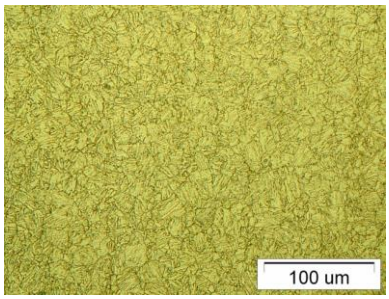


Figure 5 - Base material microstructure, original magnification 500×

Figure 5 shows base material microstructure i.e. microstructure of low-alloy high-strength steel S960 QL composed of tempered martensite of characteristic acicular shape. In some areas some fine extracted spheroidized carbides have been detected.

3. RESULTS AND DISCUSSION

Measured microhardness values are shown in graphs on figures 6 and 7.

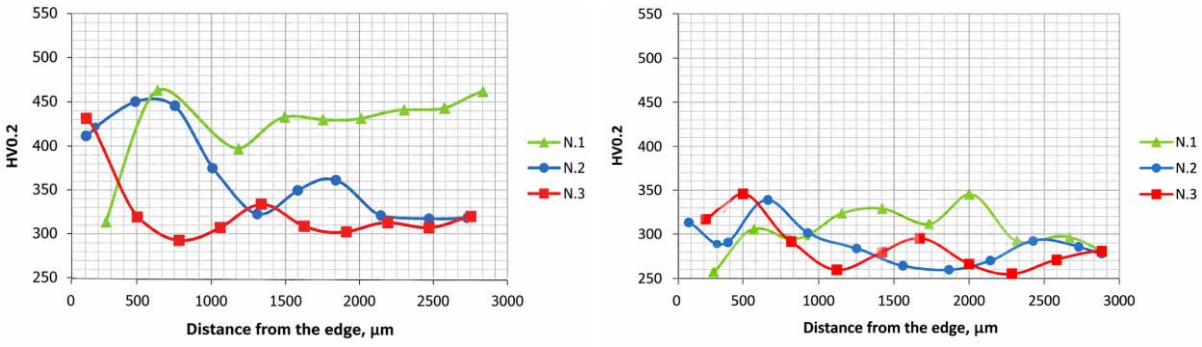


Figure 6 - Measured microhardness values for specimen AC1 (left) and AC2 (right)

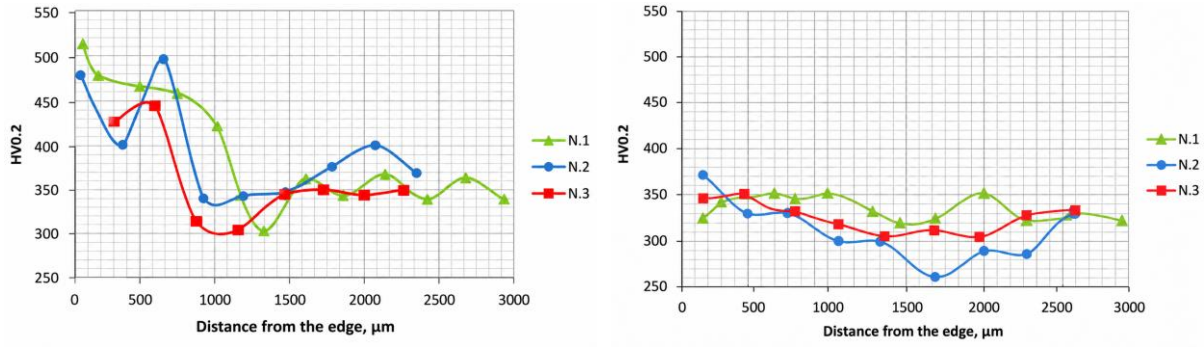


Figure 7 - Measured microhardness values for specimen PB1 (left) and PB2 (right)

Gathered microhardness testing results for oxyfuel gas cutting without preheating indicate significant hardness increase in the heat affected zone with distance of 1 mm from the cutting surface. Hardness decrease on values lower than those of base material was established in areas 1 to 1.5 mm away from cutting surface which indicates carbon diffusion from that area to the cutting surface area. This hardness increase is more noticeable when propane-butane mixture is used. In that case even maximum measured hardness values are higher than those after cutting with acetylene (~500 HV0.2 for propane-butane in comparison to ~450 HV0.2 for acetylene).

Hardness diagram for specimen AC1 does not show significant hardness decrease along upper sheet surface (measuring line N1) for measuring distance which is approximately 3 mm from the cutting surface. This is explained with the fact that heat affected zone along upper sheet surface is somewhat wider when using acetylene, so microhardness testing stayed in that area. Similar effect is detected when propane-butane mixture is used but then heat affected zone along upper sheet surface is narrower. Hardness diagram for specimen PB1 shows hardness decrease for measuring line N1 which is shifted slightly to the right.

When preheating was conducted before cutting there was no significant hardness increase in vicinity of cutting surface. Actually, hardness decrease was indicated in both cases in the entire measuring area. Hardness decrease effect is stronger when using acetylene for cutting (~270 HV0.2 when acetylene is used in comparison to ~320 HV0.2 for propane-butane). This can also be explained with temperature on the edge of the sheet which was 170°C when acetylene was used in comparison to 150 °C for propane-butane mixture). In both cases preheating temperature was obviously too high which led to general hardness decrease along cross-section. In cases where hardness increase along edges is not desirable i.e. additional machining or heat treatment, preheating temperature should be somewhat lower (75-150 °C). Images of microstructure confirm measured hardness values distribution. Grain growth is established along the cutting edge, but that effect decreases with distancing from cutting surface where grains are again normal in size and shape.

4. CONCLUSION

During this study it was verified that there are significant differences between microstructure and hardness of cutting surface and heat affected zone when cutting low-alloy, high-strength steel with acetylene when compared with those gained with cutting with use of propane-butane mixture. Different widths of heat affected zone have been detected dependent on weather material was preheated before cutting or not. When preheated heat affected zone is wider but transition from rough grain structure to base material structure is smoother. Minimum heat affected zone width was detected for oxyfuel gas cutting with propane-butane without preheating but it also caused highest hardness increase. Decarburizing of some areas along cutting edge was also noticed regardless of which type of cutting gas was used or weather

material was preheated or not. All the listed reasons indicate that this behavior should be analyzed in detail with focus on chemical composition changes of prepared metallographic specimens.

High-strength low-alloy steels are very sensitive towards preheating due to possible mechanical properties degradation so it is very important to choose appropriate preheating temperature. Correct choice of preheating temperature can reduce hardness increase in the heat affected zone. Even then some grain size growth will occur along the cutting edge which can lead to cracking. If described state of cutting surface does not meet the conditions for following processing operation such as welding it is necessary to remove that hardened layer with machining.

REFERENCES

[1] Kralj, S., Š. Andrić, Osnove zavarivačkih i srodnih postupaka, Fakultet strojarstva i brodogradnje, Zagreb, 1992.
[2] O'Brien, R. L. (Ed.), Welding Handbook, Vol. 2: Welding Processes, 8th ed., American Welding Society, Miami, 1991.
[3] Jovanović, M., M. Božović, O. Stojanović, Gasno i ručno elektrolučno zavarivanje, Građevinska knjiga, Beograd, 1979.
[4] Muñoz-Escalona, P., M. C. Payares, M. Dorta, R. Diaz, Analysis and Influence of Acetylene and Propane Gas During Oxyfuel Gas Cutting of 1045 Carbon Steel, Journal of Materials Engineering and Performance, 15 (2006), 6, pp. 684-692.
[5] Ito, Y., M. Kamo, Y. Araki, B. Miyanaga, K. Nikuma, Study on Welding of Low Alloy High Strength Steels (Report 5) – Oxy-Acetylene Gas Cutting, Journal of the Japan Welding Society, 28 (1959), 12, pp. 881-889.
[6] Dillinger Hütte GTS, DILLIMAX – Technical Information No. III/2007, Dillinger Hütte GTS, 2007, Dillingen, Germany.