Effects of Carbon and Oxyfuel Pressures on Kinetics of OFC-A of Steels.

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ABSTRACT

Oxyacetylene flame cutting is a relevant and widespread industrial process. The basic principles of the process lie in rapid high-temperature oxidation of the cut metal. The kinetics of the process depends, among other things, on the composition of the cut metal. In this present work, experimental and theoretical exposition is made on the kinetics of the OFC-A process. Report of the role of carbon on the kinetics of the process is also made. This was done by investigation of the effects of carbon content on the cutting rates of steels by the oxyacetylene cutting process.

Six 10mm steel rods of different wtpct C were flame cut using different acetylene and oxygen pressures. The composition of the steel rods used ranged from 0.16 wtpct C to 0.33 wtpct C, the acetylene pressures used ranged from 3.45 x 10^{-2} N.m^{-2} to 5.52 x 10^{-2}N.m^{-2}, while oxygen pressure ranged from 2.76 x 10^{-1}N.m^{-2} to 3.17 x 10^{-1} N.m^{-2}. The result shows that the cutting rates decreased with carbon content of the steel as a result of reduction of iron oxide during decarburization reactions. However, the flame cutting rates increased with both acetylene and oxygen pressures.

(Keywords: flame cutting, oxyfuel, oxyacetylene, steel oxidation, decarburization)

INTRODUCTION

As an industrial process, the cost of welding plays a crucial role in manufacturing decisions (Adedayo, 2009b). Many different variables affect the total cost, including equipment cost, labor cost, material cost and energy cost. Labor cost depends on deposit rate (the rate of welding), the hourly wage and the total operation time, including both time of welding and handling the part to be welded. OFC-A (oxyacetylene cutting) forms one of the significant operations carried out before the actual welding process (Adedayo 2009a). The cutting speed of the OFC-A process significantly affects the total operation time (Adedayo and Oyetoyan, 2010).

OFC-A is the American Welding Society (AWS) classification for oxyfuel gas cutting in which acetylene is the fuel (AWS, 1991). The low cost of OFC-A equipment is one of the main reasons for its use. In oxy-fuel cutting (OFC), a cutting torch is used to heat metal to kindling temperature where the metal starts to turn a cherry red. A stream of oxygen then trained on the metal combines with the metal which then flows out as an oxide slag to creat the kerf (DeGarmo et al., 1999, AWS, 1991). The OFC torch head is used to cut metal. It is similar to a welding torch, but can be identified by the oxygen blow out trigger or lever. The cut quality depends on the torch tip size, type, and distance from the metal (AWS, 1991), the oxygen and preheat gas flow rates and the cutting speed. However, the kinetics of the process will also depend on the oxidation process of the cut metal.

There has been considerable interest in the high temperature oxidation of metals. Textbooks on this subject include Birks and Meier (1983) and Kofstad (1988). When steel is exposed to high temperature oxidation conditions (Poirier, et al., 2006), a multilayer scale forms consisting of FeO (wustite), Fe_3O_4 (magnetite), and Fe_2O_3 (haematite) with the wustite layer next to the steel surface and haematite at the gas-scale interface.

Kinetics of reactions between gas and iron have been studied extensively during last three decades. Characteristic features in the mechanisms of decarburization of molten iron-carbon alloys, desorption of CO and absorption of oxygen into molten iron are fairly well understood. Sarma et al., (1996); Li and Barati, (2009); Teasdale and Hayes, (2005) ; Li, et al., (2000) , Fruehan, (2000), Mroz, (2001), and Xie, (2003) have studied the kinetics and mechanism of reduction of iron oxides by carbon and carbon compounds in slag. These studies are also found useful in many metallurgical reactions involving steel oxidation.

In this present work, the mechanism of oxidation of steel and interaction effects of carbon on the kinetics of OFC-A process is discussed. The effects of cutting pressures of the oxyfuel gases are also elucidated.

Thermodynamic analysis does not provide information on the rate of reactions in metallurgical processes (Upadhyaya and Dube, 1977). To study rates of reactions, kinetics is employed. The knowledge of kinetics of reactions/process is significant. In this present work, the mechanism of oxidation of steel and interaction effects of carbon during OFC-A process is discussed.

MATERIALS AND METHODS

This study was carried out in 2006. The hot-rolled 10mm metallurgy steel rods that were used in this study were procured from the Universal Steel Rolling Mill, Ogba-Ikeja, Lagos, Nigeria. These were cut into 0.2m long specimen. The chemical compositions of the steel rods used in this experiment are given in Table 1.

At the required pressures, a cutting torch is used to heat the steel rods surface to kindling temperature where the steel rods starts to turn a cherry red. Oxygen is then released by depressing the oxygen lever to react with the metal which then flows out of the cut (kerf) as an oxide slag. The time taken to cut the rods is noted and recorded using a stop watch. The cutting rate is calculated by finding the ratio of the diameter of rod to the total time taken i.e.:

Cutting rate = Diameter of rod / total time of cut

RESULT AND DISCUSSION

Figures 1, 2, 3, and 4 show the variations of cutting rates with carbon contents at different acetylene and oxygen pressures. From Figure 1, the cutting rate was a maximum of 2.02mm/min at 5.52 x 10^{-2}N.m^{-2} acetylene pressure and 3.17 x 10^{-1} N.m^{-2} oxygen pressure. A minimum of 1.02mm/min. was achieved at 5.52 x 10^{-2}N.m^{-2} acetylene pressure and 2.76 x 10^{-1}N.m^{-2} oxygen pressure.

In Figure 2, a maximum of 1.90mm/min was achieved at 4.83 x 10^{-2} N.m^{-2} acetylene pressure and 3.17 x 10^{-1} N.m^{-2} oxygen pressure for 0.16 wtpct C steel. The minimum of 0.91mm/min was achieved for 0.33 wtpct C steel at 4.83 x 10^{-2} N.m^{-2} acetylene pressure and 2.76 x 10^{-1}N.m^{-2} oxygen pressure.

Figure 3 shows that the maximum cutting rate is 1.82mm/min for 0.16 wtpct C steel at 4.14 x 10^{-2} N.m^{-2} acetylene and 3.17 x 10^{-1} N.m^{-2} oxygen pressure. The minimum is 0.80mm/min for 0.33 wtpct C steel at 4.14 x 10^{-2} N.m^{-2} acetylene pressure and 2.76 x 10^{-1}N.m^{-2} oxygen pressure.

Figure 4 has maximum cutting rate of 1.70 mm/min. at 3.45 x 10^{-2} N.m^{-2} acetylene pressure for 0.16 wtpct C steel. The minimum of 0.70mm/min. was achieved at 0.33 wtpct C steel at 3.45 x 10^{-2} N.m^{-2} acetylene and 2.76 x 10^{-1}N.m^{-2} oxygen pressure. Generally, the trend shows a decrease in cutting rates with increase in carbon content.

Table 1: Chemical Composition of the Hot-Rolled 10mm Metallurgy Steel Rods used for the Experiment.

SN	Alloying elements (wt%)									
	C	Si	S	P	Mn	Ni	Cr	Mo	V	W	Fe
1.	0.16	0.18	0.0589	0.0288	0.6440	0.1030	0.1244	0.0114	0.0010	0.0007	Rest
2.	0.18	0.22	0.0410	0.0237	0.7160	0.1100	0.1250	0.0220	0.0020	0.0030	Rest
3.	0.25	0.15	0.0510	0.0419	0.3658	0.01034	0.0889	0.0177	0.0003	0.0032	Rest
4.	0.28	0.18	0.0523	0.0275	0.6247	0.1170	0.1306	0.0141	0.0013	0.0035	Rest
5.	0.32	0.18	0.0576	0.0367	0.6494	0.01064	0.1550	0.0141	0.0024	0.0037	Rest
6.	0.33	0.31	0.052	0.0274	0.7523	0.1110	0.1750	0.0170	0.0030	0.0040	Rest

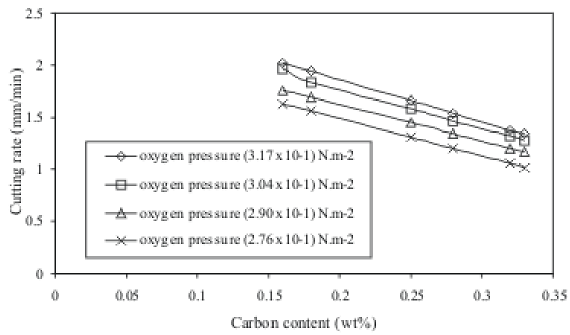

Figure 1: Variation of Cutting Rates with Carbon Content at 5.52 x 10^{-2}N.m^{-2} Acetylene Pressure.

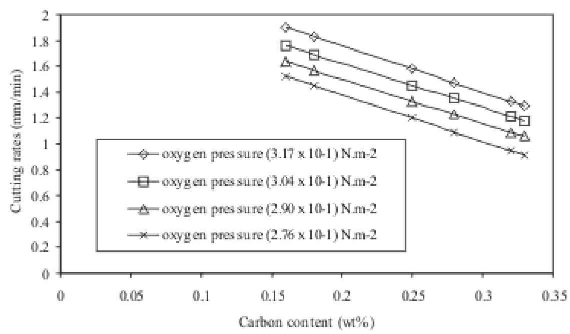

Figure 2: Variation of Cutting Rates with Carbon Content at 4.83 x 10^{-2} N.m^{-2} Acetylene Pressure.

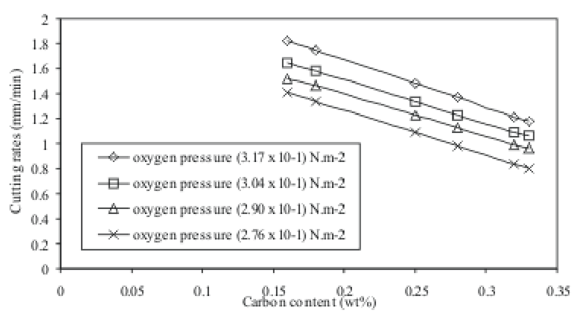

Figure 3: Variation of Cutting Rates with Carbon Content at 4.14 x 10^{-2} N.m^{-2} Acetylene Pressure.

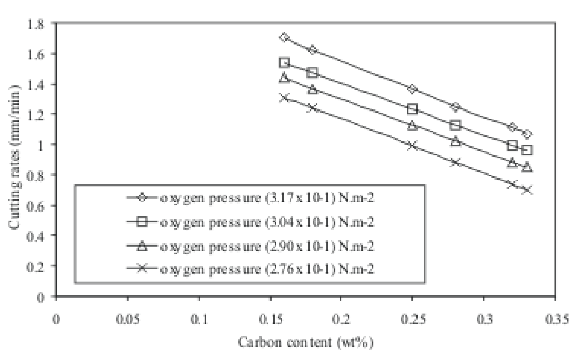

Figure 4: Variation of Cutting Rates with Carbon Content at 3.45 x 10^{-2} N.m^{-2} Acetylene Pressure.

Generally, the trend shows a decrease in cutting rate with increase in carbon content of the steel, however, cutting rate increased with cutting pressure.

If the metal being cut is non-ferrous, the metal is merely melted by the flame of the oxy-fuel gas torch and blown away to form a gap. The gap formed by this process is called kerf (DeGarmo et al., 1999). This way, the cutting rate will essentially depend on the melting point of the metal. However, when ferrous metals are being cut, the process becomes one of rapid oxidation (i.e. burning) (Masachuesset Institute of Technology 2008; Mackenzie, 1968; American Welding Society, 1987; American Welding Society, 1991) of iron at high temperature. Oxidation of metal is not simply chemical combination of metal and oxygen:

$M + ½ O_2 \rightarrow MO$ **(1)**

But consists of two partial processes:

$M \rightarrow M^{2+} + 2e^-$ (at metal-scale interface) **(2)**

½ O2 + $2e^- \rightarrow O^{2-}$ (at gas-scale interface) **(3)**

$M + ½ O_2 \rightarrow MO$ (Overall reaction) **(4)**

or,

$aM + (b/2)O_2 \rightarrow M_aO_b$ **(5)**

Oxidation of steel at temperatures higher than 843K leads to three different iron oxide layers: wustite (FeO), magnetite (Fe_3O_4) and hematite (Fe_2O_3), in oxygen content increasing order, going from substrate to free surface as illustrated in Figure 5.

Below 843K, only the last two are thermodynamically stable (Saurez et al., 2006). According to the literature, the relative thickness fractions of these layers between 973K and 1473K are 95% wustite, 4% magnetite and 1% hematite at equilibrium (Poirier et al, 2006; Suarez et al, 2006), although this balance can vary from one case to another. Depending on temperature, time, atmospheric conditions, steel chemistry, and energy barriers develop, which must be overcome for an oxide to grow (Suarez et al., 2006). Cutting by OFC-A is achieved by melting of the slag. The cutting rate in OFC-A will depend significantly on the rate of slag formation.

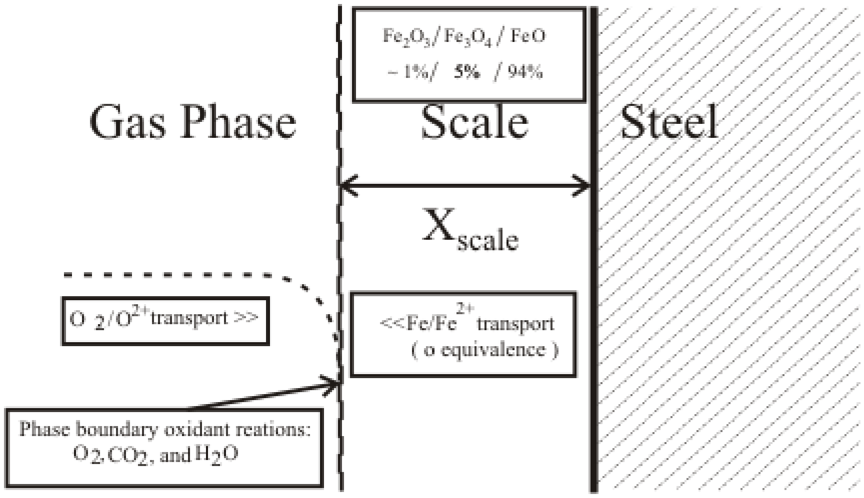

Figure 5: Mechanism of Oxidation of Steel (Poirier et al., 2006).

Any reaction that retards formation of slag affects the cutting rate. FeO is a significant proportion of products of oxidation. The retardation to the formation of FeO affects the cutting rate. Reactions below are unfavorable to the formation of FeO:

$$FeO + C \rightarrow Fe + CO \quad \textbf{(6)}$$

$$FeO + CO \rightarrow Fe + CO_2 \quad \textbf{(7)}$$

$$CO_2 + C \rightarrow 2CO \quad \textbf{(8)}$$

Min et al., (1999) and Kudrin, (1985) confirm reaction between iron oxide (FeO) and carbon (C), while Dogan, (2009) and Mori, (1988) elucidated on the reactions between iron oxide and carbon monoxide (CO), carbon monoxide and carbon.

Generally, high carbon steels are more difficult to flame cut because of the reactions between carbon, carbon monoxide, and iron oxide (Higgins, 1993; Masachuesset Institute of Technology 2008). Furthermore, carbon dissolved in metal is mainly oxidized to carbon monoxide (Kudrin, 1985). At lower carbon concentrations, however, the reaction Equation (9) must be considered in addition to the main reaction Equation (10):

$$[C] + 2[O] \rightarrow CO_{2g} \quad \textbf{(9)}$$

$$[C] + [O] \rightarrow CO_g \quad \textbf{(10)}$$

According to calculated data (Kudrin, 1985), with 0.2%[C] present in the metal, the contribution of the reaction that forms CO_2 is only 0.5%, but increases when carbon content in the metal is about 0.03%. With increase in carbon content, there is increased tendency for formation of carbon monoxide. Similar calculations have also been made by Bigeyev (1977) of the Moscow State Metallurgy Institute.

The formation of carbon monoxide reduces the cutting temperature of the flame, thus slowing down the cutting process. The standard enthalpies of formation of CO_g, CO_{2g} and CO_{2aq} at 25^0C are given as (Ebbing and Gammon, 1999):

$$CO_g = -110.5 KJ/mol \quad \textbf{(11)}$$

$$CO_{2g} = -393.5 KJ/mol \quad \textbf{(12)}$$

$$CO_{2aq} = -412.9 KJ/mol \quad \textbf{(13)}$$

Normally, a temperature of about 1200^0C is required for the cutting process to be effective (DeGarmo et al., 1999; Mackenzie, 1968; Masachuesset Institute of Technology 2008). The effect of temperature on decaburization can be estimated thermodynamically as thus (Kudrin, 1985):

a. In oxidation of carbon dissolved in the metal by dissolved oxygen:

$[C\} + [O] \rightarrow CO_g$
$\Delta G^\circ = -25000 - 37.90T$ **(14)**

b. In oxidation by iron oxide:

$[C] + (FeO)_l \rightarrow Fe_l + CO_g$
$\Delta G^\circ = + 115000 - 98.18T$ **(15)**

c. In direct oxidation by oxygen:

$[C] + 1/2O_{2g} \rightarrow CO_g$
$\Delta G^\circ = -142000 - 40.79T$ **(16)**

Thus in all the cases, the free energy change ΔG° decreases with temperature (i.e. more favorable conditions are formed for carbon oxidation). The rates of reaction always increase at higher temperatures, considering the circumstance that the reaction of carbon monoxide is practically irreversible, since the gases produced by this reaction is removed continuously from the reaction zone. Also, cutting rate has been shown to increase with temperature (Powell et al., 2009). This is illustrated in Figure 6.

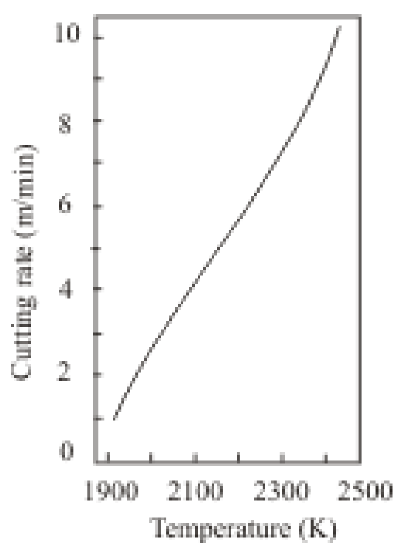

Figure 6: A Typical Relationship between Cut Front Temperature and Cutting Rate (Powell et al., 2009).

The increase in cutting rate witnessed as a result of increase in acetylene and oxygen pressure is due to the increase in kinetic energy of the gas stream used in expelling liquid iron oxide from the cut-surface to form a kerf. Also, the combustion of acetylene flame consists of different stages which include:

a. $2C_2H_2 + 2O_2 \rightarrow 4CO + 2H_2$ **(17)**

b. $4CO + 2H_2 + 3O_2 \rightarrow 4CO_2 + 2H_2$ **(18)**

The first stage (Equation 17) uses the oxygen supplied from the acetylene mixture, and available in the oxyacetylene mixture. The reaction is seen as the small inner cone of the flame (American Society for Metals, 1971).

The highest temperature is at the point of this cone. The second stage (Equation 18) uses oxygen supplied from the air surrounding the flame. It may be seen that about two-fifth of the oxygen necessary for the complete combustion of acetylene comes from the oxygen cylinder when the flame is neutral. The remainder comes from the air around. When the oxygen pressure is increased, this increases the amount of oxygen available for the reaction of the second stage, thus increasing the speed of the flame cutting process.

CONCLUSION

Generally, the cutting rates decreased with carbon content of the steel. At the same oxygen pressure, cutting rates have decreased up until about 65% with increase in carbon content of about 0.17wt%. The reason for the observed trend being the increased tendency for formation of carbon monoxide as carbon content increased. Increased cutting pressures of acetylene and oxygen lead to increased cutting rates.

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