Residual Stresses in the Heat Affected Zones of Flame Cut Steel Plates

By K. N. RAO*

1. Introduction

Residual stresses may be defined[1] as those stresses which exist in a material free of external load, generally resulting from nonhomogeneous plastic deformation which may be introduced in many ways such as fabrication process, flame cutting, welding etc. During the flame cutting process, there is a rapid change in temperature, resulting in non uniform heating and cooling which not only introduces residual stresses but also causes changes in chemical composition of the material in the region of the edges of cut. When the heat is conducted to the surrounding parent material, rapid rates of cooling are encountered. In addition, the varying degree of affinity of iron and the various alloying elements in steel to oxygen gives rise to changes in the chemical composition of the material in the neighbourhood of the cutting area.

The usual methods of studying the residual stresses in flat surfaces employ plates of uniform cross section of sufficient length to give deflections which can be measured by mechanical methods. In order to limit the stresses to uniaxial stress distribution, it is customary to select specimens which are long enough in comparison with the dimensions of the cross section.

Leiris and Ballet[2] have investigated the distribution of residual stresses in mild and nickel-chromium steels using mechanical and optical methods. For mechanical method, mild steel specimen 4 metres long, 400 mm high and 31 mm thick was used. The curvature measurements were made in a length of one metre using a comparator with an accuracy of 0.001 mm.

Using optical method, the investigation was carried out on 720 mm long, 49.5 mm high and 9 mm thick Nickel-chromium steel specimen. Steps of about 1 mm thick layers of surface were cut in milling machine and then the surface was filed before taking a reading. This investigation revealed a tensile residual stress on the surface of the flame cut in the case of mild steel and a compressive residual stress in Nickel-chromium steel. However, the exact composition of the materials used and the thickness of the layer removed in mechanical method are not stated in Leiris and Ballet investigations.

Ruge and Krahl[3] have investigated the cold working properties of the heat affected zone resulting from flame cut steel sheet metals. The residual stresses in flame cut plates of 15 mm thick steel St 52-3 specimens were investigated by removing metal layer by layer in planing machine. The presence of compressive residual stress on the flame cut surface was explained due to the formation of martensite. The above mentioned two investigators [2,3] calculated the residual stresses using Treuting and Read formula[1] and using graphical methods for the computation of differentiation and integration. In his paper[4] on the cold working properties of flame cut components, Ruge has predicted the distribution of residual stresses in flame cut St. 52-3 steel plates in the zone of cut. Hitherto, all the authors have used the equations derived by Treuting and Read, Letner or Stablein and the computations were carried out graphically. Present investigation was carried out elaborately with the object of determining the residual stress distribution in the zone nearer to flame cut. Two materials, one with very low carbon content (Armco iron) and the other with 0.38 per cent carbon content were chosen for the present investigation.

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2. Preparation of specimens and measurement of deflection

Details of the materials used :

Steel St-60 : This steel showed the following analysis.

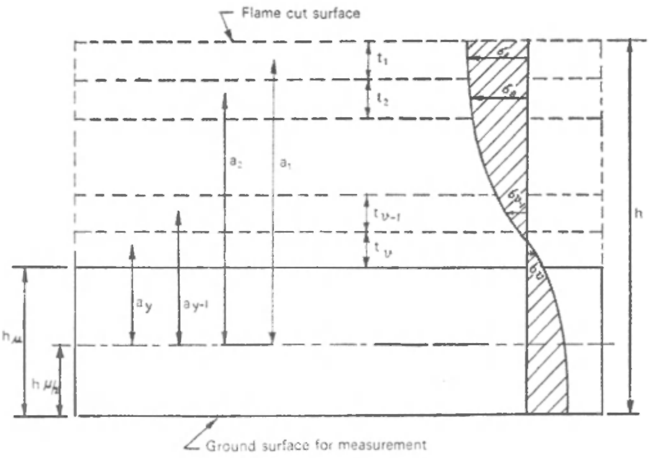
Element	C	Mn	Si	S	P
Content, %	0.377	0.635	0.242	0.032	0.011

Armco iron : This material has the following composition :

Element	C	Mn	Si	S	P
Content, %	0.020	0.035	0.002	0.025	0.015

Plates 300 mm long, 250 mm wide and 10 mm thick were saw cut from a large plate and stress relieved in the furnace by heating them upto 650°C and holding them at this temperature for one hour followed by furnace cooling. These plates were flame cut in the middle in such a manner that two plates of 250×150×10 mm were obtained from each of the annealed plates. For the purpose of flame cutting, a combination of one cutting speed and one flame size was selected for each plate. Two cutting speeds and two flame sizes were selected. In this manner eight specimens were obtained for each material, two of them being exactly identical. During short and long flame sizes the pressures of oxygen and acetylene were maintained constant. The cutting jet used in all the cases was ARS 10 ... 25 with a distance of the jet 8 mm away from the surface of the plate. The cutting speeds selected were normal speed of 500 mm/min and a speed of about half the normal speed, 200 mm/min.

All the specimens were at first saw cut on the edge opposite to the flame cut to a height slightly more than 40 mm and then the saw cut surface was ground. The ground surface was used as the measuring surface. The final heights of the specimens were kept as 40 mm. The initial deflection in a length of 200 mm and the average height of the specimens were noted before starting the machining operation. The flame cut surface was gradually machined in a surface grinding machine. Layers of about 0.20 mm depth were machined in small steps, keeping the plate constantly under a stream of coolant. After each layer, the specimens were allowed to cool and then the deflection in a length of 200 mm and the average height of specimen were determined at room temperature in the unconstrained position. The layer removal process was continued upto a depth of about 5 mm below the flame cut surface. Residual stresses in each layer were calculated using the derived Recurrence formula of Art 3.



$a_1=(h+t_2+t_3+ \dots\dots +t_v)/2$
$a_2=(h-t_1+t_3+t_4 \dots\dots +t_v)/2$
$a_\mu=(h-t_1-t_2 \dots\dots t_{\mu-1}+t_{\mu+1}+\dots 1t_y)$

Fig. 1. Representation of 'a' in terms of 'h' and 't'

3. Recurrence formula for the determination of Residual Stresses in a rectangular plate :

Consider a simple rectangular plate (fig. 1) with one of its sides flame cut and the other side ground so that it can be used as a measuring surface. During the flame cutting process residual stresses are introduced longitudinally so that the distribution of stresses across the height 'h' can be determined by removing layer by layer along its length 'l'.

Considering the first layer and balancing the forces and moments we have,

$$\triangle M = \sigma_1 t_1 b h/2 \quad \dots\dots \quad 1$$

where, $\triangle M$ = balancing moment, b = width of the specimen.

σ_1 = residual stress in a layer of thickness t_1

Expressing the moment as a change in curvature and using equation 1, the following equation can be obtained :

$$\sigma_1 = \frac{E(h-t_1)^3}{6\, t_1\, h}\left(\frac{1}{\rho}-\frac{1}{\rho_1}\right) \dots\dots \quad 2$$

where ρ and ρ_1 are the initial curvature and the curvature obtained after the first layer removal respectively.

Such formulas have been developed by Walter Leaf[5]. Expressing the curvature in terms of defections and the distances from the centre of the removed layers

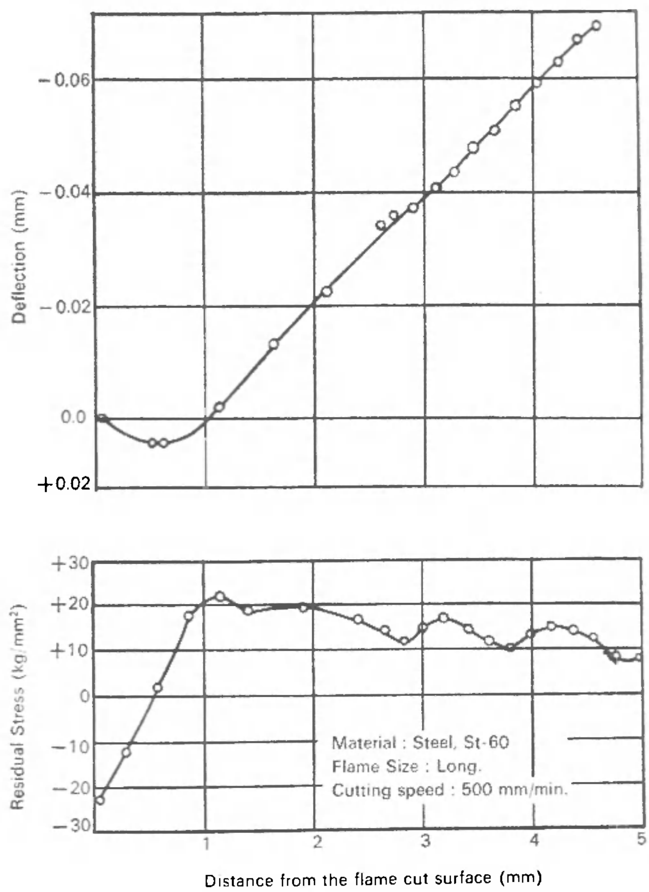


Fig. 2. Residul stress in the direction of cutting

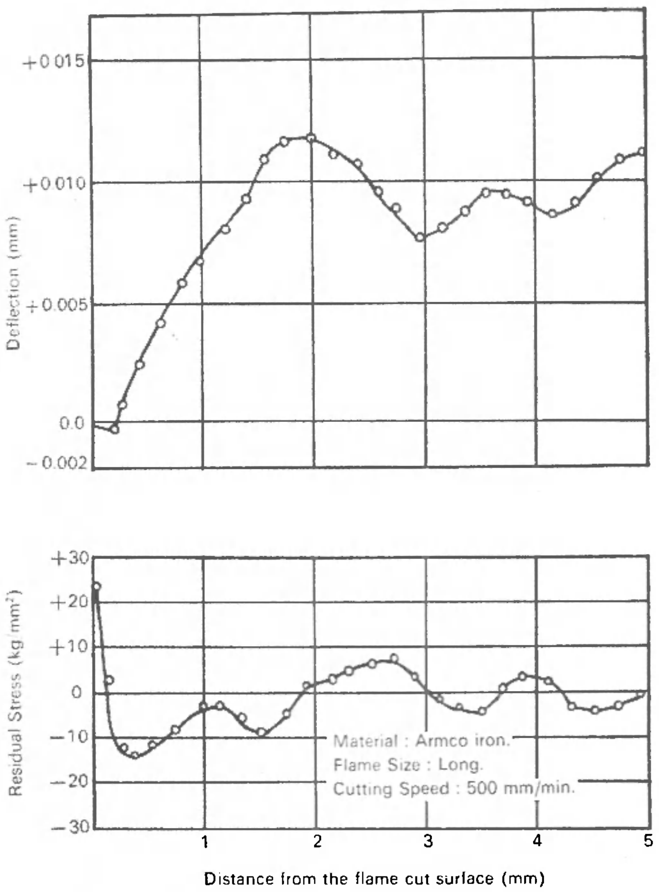


Fig. 3. Residul stress in the direction of cutting

(a_1, a_2, ... $a_\wp$) in terms of original height and the thickness of the removed layers (as shown in fig. (1)), the final equation for residual stress at any height can be obtained as :

$$\sigma_\wp = \frac{Ea^2}{3} \frac{(h - t_1 - t_2 \ldots\ldots t_\wp)^3 \ (s - s_\wp)}{(a^2 + sh)\ [a^2 + s_\wp\ (h - t_1 - t_2 \ \ldots\ldots t_\wp)]} - \frac{\sum_{\mu=1}^{\wp-1} (h - t_1 - t_2 \ldots\ldots t_{\mu-1} + t_{\mu+1} + \ldots\ldots + t_\wp)}{t_\wp\ (h - t_1 - t_2 \ldots\ldots\ldots - t_{\wp-1})} \qquad \ldots\ldots\ldots 3$$

where

$\sigma_\wp$ = Residual stress after '$\wp$' layers of removal in kg/mm²

E = Modulus of elasticity in kg/mm²

$s_1, s_2, \ldots\ldots s_\wp$ = Measured deflections in first, second, ... $\wp$th layer removal in a distance of "2a" (mm)

$t_1, t_2, \ldots\ldots t_\wp$ = Thickness of layers removed.

From the equation 3, the stress in the first layer is given by,

$$\sigma_1 = \frac{Ea^2h}{3(a^2 + sh)^2} (s - s_1) \qquad \ldots\ldots\ldots 4$$

If the first layer is very thin, then σ_1, will be residual stress very near to the surface of flame cut.

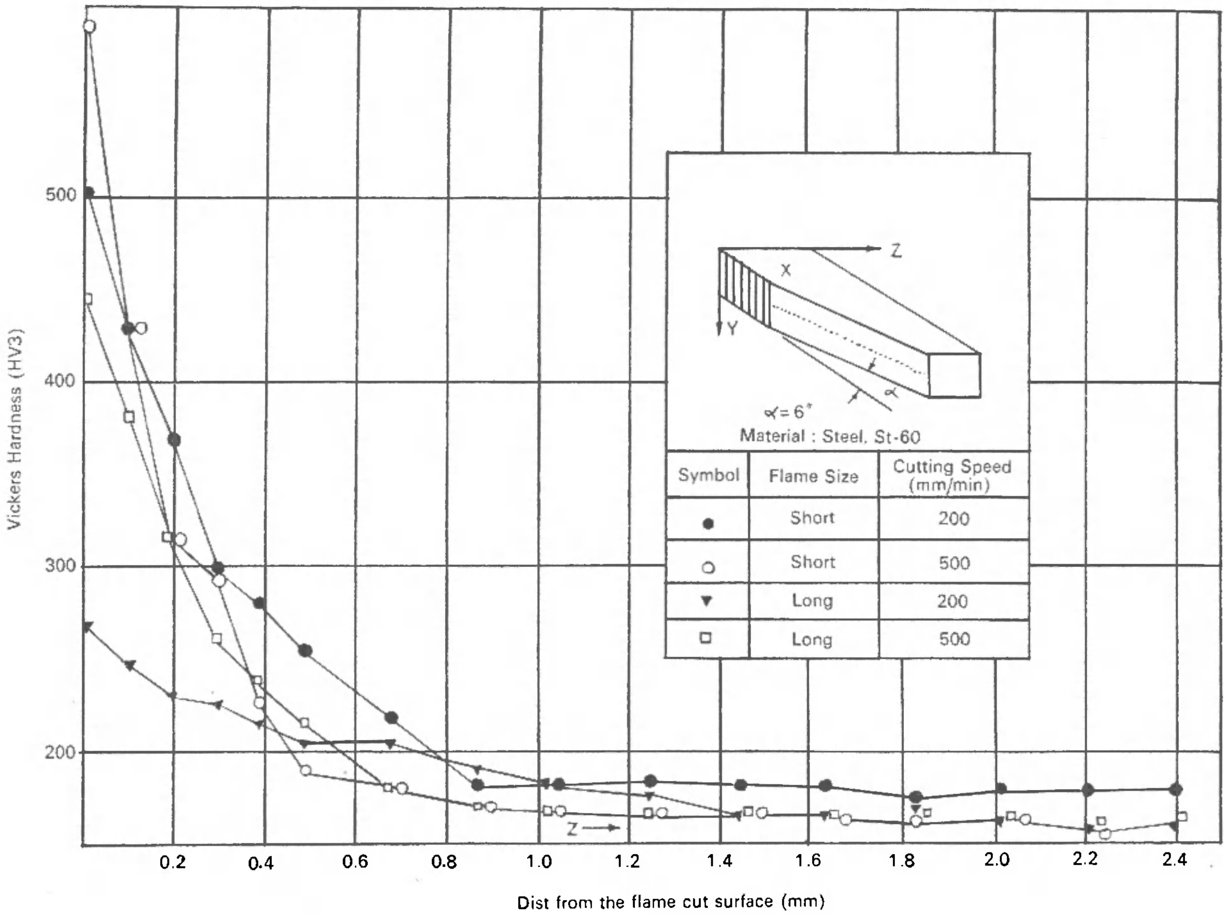
The expression 3 does not involve differentiation or integration as such it is easily amenable to numerical calculations.

To eliminate the experimental scatter in the measured values, smoothing formulas have been used. A computer programme was developed to calculate the residual stresses.

4. Discussion of Results :

4.1 *Residual stresses*

Figs. 2 and 3 show the distribution of residual stresses in the heat affected zones of Armco iron and steel St-60 cut at normal speed.



Symbol	Flame Size	Cutting Speed (mm/min)
●	Short	200
○	Short	500
▼	Long	200
□	Long	500

Fig. 4. Variation of hardness in heat affected zone.

Figs. 4 and 5 show the variation of hardness values in the heat affected zones of Armco iron and steel st-60 cut at different conditions.

In Steel st-60 specimen, compressive residual stresses occur on the surface of cut whose value is about 23 kg/mm. This value of stress coincides to a great extent with the findings of Leiris and Ballet. Normally in flame cutting and welding, the maximum residual stresses encountered will be equal to the yield stress of the parent material. The compressive residual stress on the surface of flame cut may be due to the volume change caused by the formation of Martensite near the zone cut[3]. Immediately after the zone of compressive stress, highest value of tensile stresses occurs at about 1 mm from the cut edge. Thereafter the tensile zone prevails upto the investigated zone.

In Armco iron specimen, tensile residual stresses of the value 24 kg/mm^2 are encountered on the surface of the cut. This value also very well coincides with the findings of Leiris and Ballet[2]. The occurence of tensile residual stress on the surface of low carbon material is because of the nonformation of martensite. Normally the maximum value of residual tensile stress encountered in low carbon materials is equal to the tensile stress of the parent material. At about a distance of 0.4 mm from the cut surface, the residual stress becomes compressive but thereafter the value of stress oscillates between compressive and tensile.

Both the materials show a similar stress pattern reaching three times maximum and three times minimum value.

Hardness

Tapered specimens as shown in figs 4 and 5 were prepared and the Vickers hardness measurements were found out at the mid thickness of the specimens in the heat affected zones. The following observations were made :

(i) There is a steep fall in hardness values as one travels from flame cut edge towards the centre of the plate. The length of the heat affected zone is about 0.8 mm.

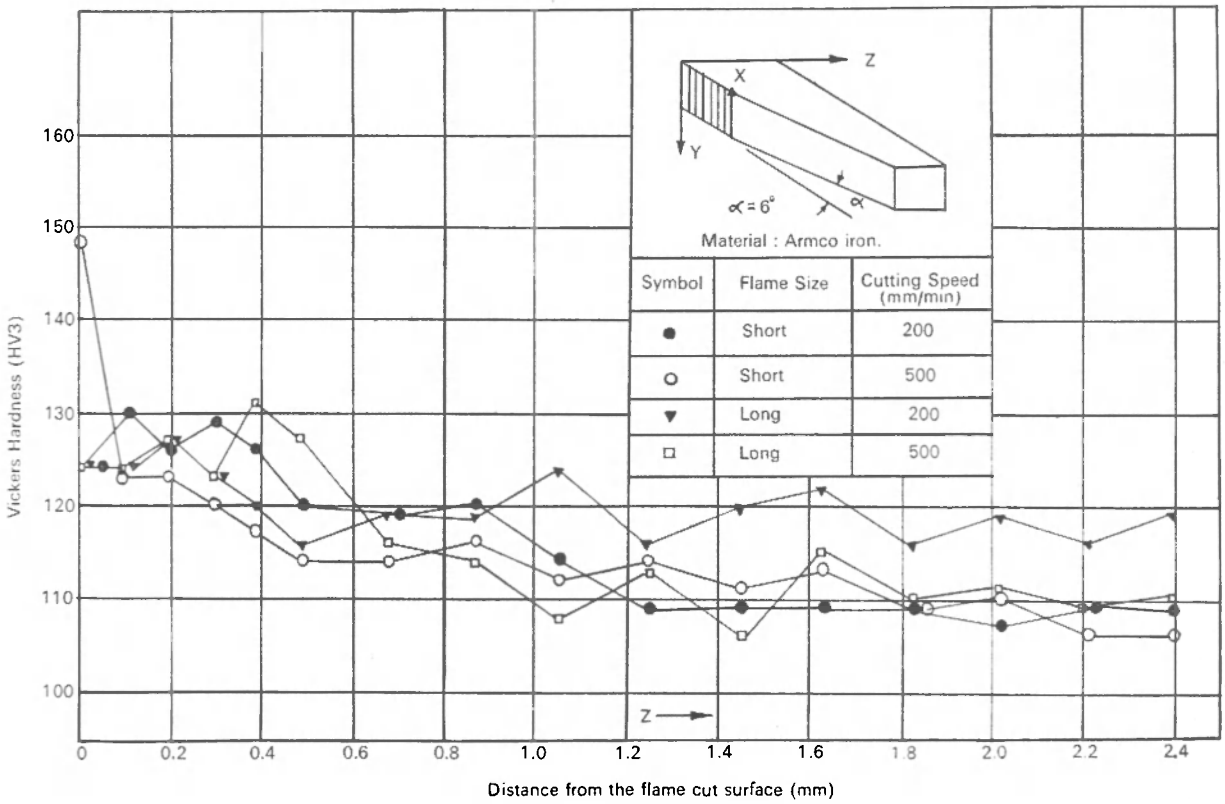


Fig. 5.

(ii) The increase in hardness values in Armco iron is comparatively small. The increase in hardness depends on the degree of carburisation in the cut zone which in turn depends on the carbon content in parent material[9]

(iii) Hardness values increase with the increase in the cutting speed as observed by Reeve and Maw[11].

(iv) Keeping the cutting speed constant if the flame size is varied (short or long), the shorter flame introduces higher hardness values than long flames. This may be due to greater heat input to the plate by short flames.

Structure :

Steel St-**60**

Microscopic examination of the external zone revealed localised melting of 10 to 20 mm width in the zone of cut. Immediately after this layer, was found in a narrow area, residual austenite followed by Martensite, fine Pearlite and Ferrite. Finally, this merged into the structure of the unchanged parent material.

Armco iron

Different grain sizes of ferrite could be observed. No martensite structure could be identified.

5. Conclusion

From the present investigation the following conclusions may be drawn :

(1) Expression 3 gives a simple formula for the determination of residual stresses. As the expression does not involve differential coefficient or integral it is easier to calculate the stresses.

(2) Compressive residual stresses are encountered in high carbon on the surface of flame cut.

(3) Tensile residual stresses occur on the surface in the case of low carbon materials.

(4) The hardness values in the heat affected zone depend on the carbon content in the parent material, speed of cutting and rate of cooling.

6. Acknowledgement :

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