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MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

# APPLICATION OF CRACKABILITY PARAMETERS TO EVALUATE TEST RESULTS OF SELF-RESTRAINED CRACKING SPECIMENS

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## ABSTRACT

Weld cracking susceptibility, or simply, the weldability, is a most significant problem in utilizing high strength steels. A number of formulas have been suggested and available for the prediction of the weldability using chemical composition. Those formulas calculate various weldability criteria such as the hardness, the ductility and the amount of cracking in the heat affected zone. Ito and Bessyo have proposed crackability formulas ($P_c$ and/or $P_w$) including chemical composition, weld metal hydrogen content, plate thickness and stress-intensity. In their work they have used the y-groove restraint cracking test specimen.

In this investigation, an attempt was made to evaluate test results of Tekken, Lehigh and CTS using the proposed parameters. Structural steels of different chemical composition and thickness were welded, using electrode diameters from 3.25 to 5.0 mm. Welding current was varied from 120 to 220A and welding speed from 8 to 20 cm/min. Preheating temperature range was from 25 to 150°C. Cracks were detected and evaluated in three to four transverse sections of test welds.

Test results obtained using Tekken, Lehigh and CTS crackability tests are compared and evaluated. Critical cooling time between 800 and 500°C was determined for each test condition using crackability parameters $P_c$ and/or $P_w$ at which crack formation starts in the welded joints. Simultanously, the abovementioned tests were ranked from severity point of view.

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INTRODUCTION

Cold cracking in weld heat affected zone (HAZ), has a metallurgical as well as mechanical causes. The initiation of this type of cracking depends upon the simultaneous operation of the following factors;

- the formation of susceptible microstructure,
- the presence of hydrogen,
- the development of welding stresses.

When these conditions prevail, cracking can take place at a relatively low temperature, as a number of causes have shown, evensome time after welding.

The interrelation between the above mentioned factors are complicated, and test methods have been developed tc study the effect of each factor. The interrelation between the factors affecting cold cracking susceptibility was given in earlier work |1,2|. The mechanism and kinetics of dislocation movement and its relation with cold crack formation was discussed |3|.

Cold cracking tests were discussed and limitations of same tests were investigated. The stresses generated in some test specimens have been analysed to determine their influence on test results |4|.

Empirical relations were introduced to overcome cold cracking in C-Mn and microalloyed steels |5| using self-restrained and externally restrained test specimens. Application of these relations on actual welded structures to determine the limiting values of critical stresses was performed. On the basis of experimental results nomograms were prepared to predict safe welding conditions to avoid cold cracking in single, first and multilayer welding |6|.

A number of weldability formulas have been proposed to estimate the weld cracking susceptibility of various steels. All the formulas developed are relating the cracking susceptibility to the hardenability of the steel. The proposed formulas by Ito and Bessyo |7,8| are dependent on the chemical composition, the diffusable hydrogen in weld-metal and the plate thickness or the intensity of restraint. In their investigation, they have used the y-groove restraint cracking test specimen, and correlated the results by the coding time from 300 to 100°C.

The aim of this work is to evaluate test results of Tekken, Lehigh and CTS tests using the proposed parameters ($P_C$ and $P_W$). At the same time, critical cooling time between 800 and 500°C is to be determined, for prediction of safe welding conditions to avoid cold cracking in welded structures.

## Crackability Parameters

One of the bestknown equation to estimate the heat affected zone (HAZ) hardness is the one presented by Dearden and O'Neill in 1940 |9|.

$$C_e = C + \frac{Mn}{6} + \frac{Si}{15} + \frac{Cr}{5} + \frac{Mo}{4} \qquad (1)$$

The hardness developed in the HAZ of Reeve test is linearly proportional to the carbon equivalent calculated by this formula. Dreaden and O'Neill are also giving an equation, (2), which is applied to fillet welds on 12 mm thick plates ;

$$D.P.N. = 1,200\ C_e - 200 \qquad (2)$$

Kihara, Suzuki and Tamura modified Eq.(1) and proposed the carbon equivalent expressed by Eq.(3) |10|,

$$C_e = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} \qquad (3)$$

Equation (4) gives the relationship between the maximum hardness and the carbon equivalent calculated by Eq.(3)

$$H_{max.} = (666\ C_e + 40) \pm 40 \qquad (4)$$

The carbon equivalent furmula Eq.(3) another additional term, + V/14 and is commonly used in Japan. This is adapted in Japan Industrial Standards (J1S) for structural rolled steels.

Bradstreet |11| studied the relationship between the alloying elements and the end of transformation temperature and suggested an equation of carbon equivalent, Eq.(5).

$$C_e = C + \frac{Mn}{20} + \frac{Ni}{15} + \frac{Cr+Mo+V}{10} \qquad (5)$$

Winterton |12| suggested Eq.(6), according to the relationship between 90% transformation temperature ($M_{90}$) and alloying elements ,

$$C_e = C + \frac{Mn}{6} + \frac{Ni}{20} + \frac{Cr}{10} - \frac{Mo}{50} - \frac{V}{10} + \frac{Cu}{40} \qquad (6)$$

Equation (7) has been suggested in IIW Commission 1X; Sub-Commission G |13|.

$$C_e = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} \qquad (7)$$

It is reported that, this equation should be applied for determining weldability of carbon and carbon-manganese steels together with the relationship $H_{max} < 350$ for either case.

Ito and Bessyo | 7 | proposed a weldability formula using y-groove restraint cracking test specimens, Eq.(8).

$$P_c = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B + \frac{t}{600} + \frac{H}{60} \qquad (8)$$

This equation includes the effect of plate thickness in (mm) and diffusable hydrogen content in addition to base metal chemical composition. At the same time, it is reported that the preheating temperature to prevent cold cracking can be evaluated by Eq.(9)

$$T(^{o}C) = 1440\ P_c - 392 \quad (9)$$

Another work carried out by the authers [8], weldability formula based on the intensity of restraint (kg/mm.mm) instead of plate thickness is given in Eq.10.

$$P_w = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B + \frac{H}{40} + \frac{K}{40x10^3} \quad (10)$$

In equations (8) and (10), plate thickness (t) in mms and weld metal diffusable hydrogen content (H) is measured using glycerine as collecting media.

## EXPERIMENTAL PROCEDURE

Experiments were carried out on Tekken [14-18,24], Lehigh [15,19,20,24] and CTS [21-24] crackability tests (Fig.1). Base materials used in this investigation are high-strength low-alloy steels of 12 and 30 mm thickness. Chemical composition of base materials is presented in Table,1. All these steels are in the normalised state.

Welding was carried out using low-hydrogen basic coated electrodes AWS-E 7016 of 3.25,4 and 5 mm diameter. All electrodes were dried at a temperature of 300-350°C for one hour before use.

Table 1. Chemical Composition of Base Metals.

| | C | Mn | Si | S | P | Ni | Cr | Cu | Mo | V | AL | Ti | B | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.18 | 1.42 | 0.5 | 0.019 | 0.023 | — | — | — | — | 0.14 | 0.027 | — | — | 0.014 |
| 2 | 0.23 | 1.38 | 0.24 | 0.021 | 0.023 | — | — | — | — | 0.16 | 0.013 | — | — | 0.007 |
| 3 | 0.05 | 0.42 | 0.5 | 0.019 | 0.064 | 0.52 | 0.68 | 0.44 | — | — | 0.01 | 0.09 | — | 0.004 |
| 4 | 0.16 | 1.5 | 0.3 | 0.012 | 0.021 | — | 1.46 | — | 0.56 | — | — | — | 0.004 | — |
| 5 | 0.09 | 0.84 | 0.57 | 0.015 | 0.051 | 1.06 | 0.84 | — | 0.62 | 0.08 | 0.063 | 0.05 | — | — |

A wide range of welding parameters was used. Welding current was varied from 120 to 220A, and welding speed from 8 to 20 cm/min. Preheating temperature ranged from 25 to 150°C were used. Cracks were detected and evaluated in three transverse sections of test welds, at enlargement up to 300X.

Weld metal diffusable hydrogen content was measured, and values of intensity of restraint were calculated. The values of crackability parameters $P_c$ and $P_w$ were calculated for each case. Cooling time from 800 to 500°C was calculated for each case.

### Weld Metal Diffusable Hydrogen

Weld metal diffusable hydrogen content of used electrodes was measured according to IIW method |25,26|. This value was found $H_{IIW}$ = 5 ml/100g. As the Eqs.8 and 10 were based on values of weld metal diffusable hydrogen content according to JIS i.e. glyserine method. The obtained value was calculated according to Eq.11. |27| ;

$$H_{JIS} = 0.79\,H_{IIW} - 1.73 \tag{11}$$

Weld metal diffusable hydrogen content $H_{JIS}$ = 2.2 ml/100g. and this value was used in calculation of $P_c$ and $P_w$ values.

## Intensity of Restraint

The values of intensity of restraint (K) were calculated according to the relations given in the liturature |32-35|. In case of Tekken test specimen, the relation between intensity of restraint and material thickness was calculated using finite element method |28,29|. This relation is given in Eq.12.

$$K = 113\ h \tag{12}$$

For Lehigh test specimen, an experimental relation between intensity of restraint (K) and material thickness (h) as follows ;

$$K = 75\ h \tag{13}$$

As intensity of restraint cannot be determined for CTS test, the crackability parameter $P_c$ was employed. Comparison between the values of $P_w$ and $P_c$ for the Tekken and Lehigh croschability tests shows that these values do not differ markedly for the used materials. For used steels the values of $P_c$ and/or $P_w$ were calculated according to Eqns 8 and i.e. in each case.

## Calculation of Cooling Time from 800 to 500°C

Cooling cycle for individual welding conditions was defined by the cooling time from 800 to 500°C. This time is being characteristic for the formation and decomposition structures in the heat affected zone, and used for general definition of the welding conditions. Cooling time from 800 to 500°C was calculated on the basis of heat distribution calculations by Rykalin |30|. Critical thickness can be calculated by Eq.14. when calculation of cooling time from $T_2$ to $T_1$ ;

$$h_{cr} = \sqrt{\frac{Q_e}{2\gamma c}\left(\frac{1}{T_2-T_1} + \frac{1}{T_1-T_o}\right)} \tag{14}$$

cooling time in case of $h<h_{cr}$ as follows ;

$$\Delta t_{T_2-T_1} = \frac{(Q_e/h)^2}{4\,\pi\lambda c\gamma}\left|\left(\frac{1}{T_1-T_o}\right)^2-\left(\frac{1}{T_2-T_o}\right)^2\right| \tag{15}$$

and if $h>h_{cr}$

$$\Delta t_{T_2-T_1} = \frac{Q_e}{2\pi\lambda}\left|\frac{1}{T_1-T_o} - \frac{1}{T_2-T_o}\right| \tag{16}$$

where : $Q_e$ = effective heat energy input per unit length of weld.
= f Q   f = joint type factor
= 1 for butt joints
= 2/3 for Lap joints.
h = plate thickness
$T_o$ = initial temperature i.e room temperature or preheating temperature.
$\lambda$ = thermal conductivity of the material
$c\gamma$ = volumetric specific heat.

## RESULTS AND DISCUSSION

Microstructural examination of sections prepared from Tekken, Lehigh and CTS crackability test specimens was carried out. Some examples of cracked sections are presented in Fig.2. It was observed that same cracks are transgranular Fig.2.C.

Calculated values of the parameter $P_w$ are plotted at different cooling time ($\Delta t_{800-500}$) for Tekken and Lehigh test specimens, Fig.3,4. The black points and white ones represent specimens without cracks. It can be seen that, all the results form two zones which can almost precisely be devided by a straight line. This line can be considered as a limiting one from the viewpoint of crack occurrence. The results obtained in the CTS test are shown in Fig.5. In this case crackability parameter $P_c$ is plotted at different cooling time ($\Delta t_{800-500}$). In this case we have a similar function.

In each case, the relation between the base material chemical composition and thickness or intensity of restraint, filler material as expressed in weld metal hydrogrn content and the technological factors showed a good relation (Fig.6). Technological factors; which are current, voltage, welding speed, material thickness, type of joint and preheat are expressed in terms of cooling time from 800 to 500°C.

Fig.6. shows that, in all cases as the values of $P_c$ and/or $P_w$ increases, the necessary cooling time from 800 to 500°C has to be increased to avoid cold cracking in weld heat affected zone. The necessary cooling time ($\Delta t_{800-500}$) is always larger in Tekken test than that in Lehigh and CTS tests for the same values of $P_c$ or $P_w$. It means that the TekKen crackability test is more severe than the other two tests.

Comparison between the results obtained from Tekken and Lehigh tests, it is observed that, Tekken test is more sensible to mutual changes in $\Delta t_{800-500}$ with respect to the change in $P_w$ values. This may be due to, the differences in groove shapes of the two test specimens. The y-groove in Tekken test may result in notch-like defect of about 40-50° directed towards the heat affected zone. Whilest in Lehigh test the Y-groove results in notch-like defect of about 80° directed towards the weld metal. This can lead to the conclusion, that the Lehigh test specimen is more suitable for weld metal evaluation than base material.

Regardless of the scatter in CTS test results, it can be seen that, as the values of $P_c$ increases, the necessary cooling time $\Delta t_{800-500}$ to avoid cold crack formation increases. For the same $P_c$ and/or $P_w$ a longer cooling time $\Delta t_{800-500}$ in case of Tekken than CTS tests. This may be due to variation in joint configuration, which affects the shape of cracking origin.

Welding technology parameters can be chosen by the help of limit lines of crack initiation. For given steel chemical composition and material thickness, the value of critical cooling time $\Delta t_{800-500}$ can be chosen, and welding variables can be planned in order to avoid cold crack formation. This can be performed according to the joint shape in which Tekken test results can be used for the first pass in multilayer welding. Lehigh test results are used in Y-shaped joints, while CTS test results is used in T-joints. The following empirical relations can be used to determine critical cooling time $\Delta t_{800-500}{}^{\circ}C$;

$$\text{Tekken} \quad \Delta t_{800-500} = 28.6 \; P_w - 3.7$$
$$\text{Lehigh} \quad \Delta t_{800-500} = 8.3 \; P_w + 1.18$$
$$\text{CTS} \quad \Delta t_{800-500} = 16.7 \; P_c - 3.0$$

## CONCLUSIONS

Three cold cracking test specimens, Tekken, Lehigh and CTS tests were used to study cold cracking susceptibility of Low-alloy high strength steels. Tests were performed for a wide range of heat input and preheat. Test results were evaluated using the crackability parameters $P_c$ and $P_w$, proposed by Ito and Bessya. The following conclusions can be stated as follows :

1) Critical cooling time $\Delta t_{800-500}$ for different values of $P_c$ and $P_w$ to avoid cold crack formation in weld HAZ was determined for each crackability test. These values can be used to chose safe welding conditions in welded joints.

2) Tekken crackability test requires longer cooling time ($\Delta t_{800-500}$) than both behigh and CTS tests. Tekken test is more sensitive to $P_w$ variation than Lehigh test.

3) Lehigh crackability test is more suitable for weld metal testing than base material.

4) Tekken test results can be used to predict safe welding conditions to avoid cold cracking in first pass of multilayer welding. While CTS test results can be applied in case of lap and T-joints.

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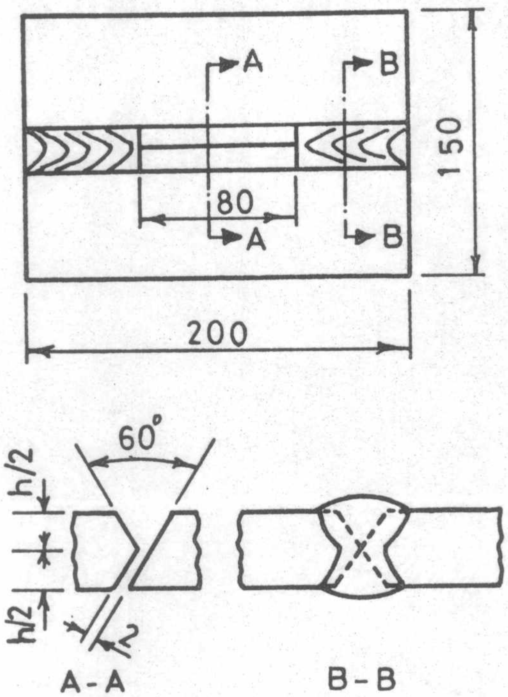
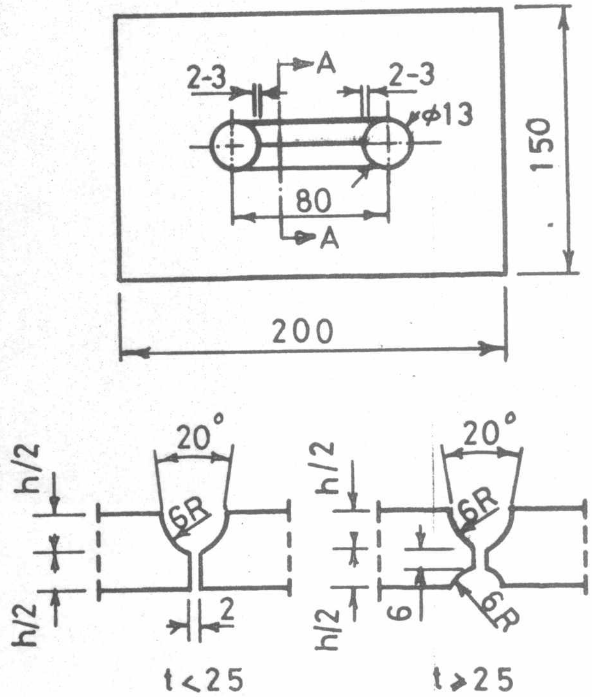
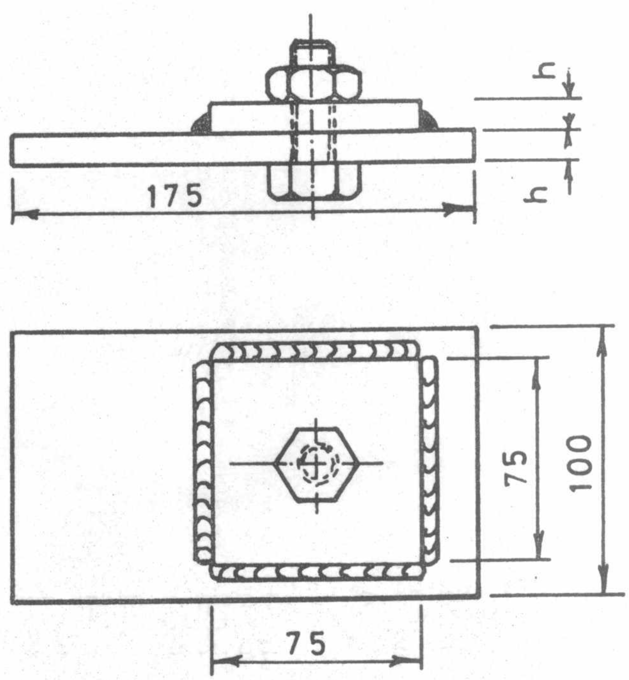



A) TEKKEN CRACKING SPECIMEN

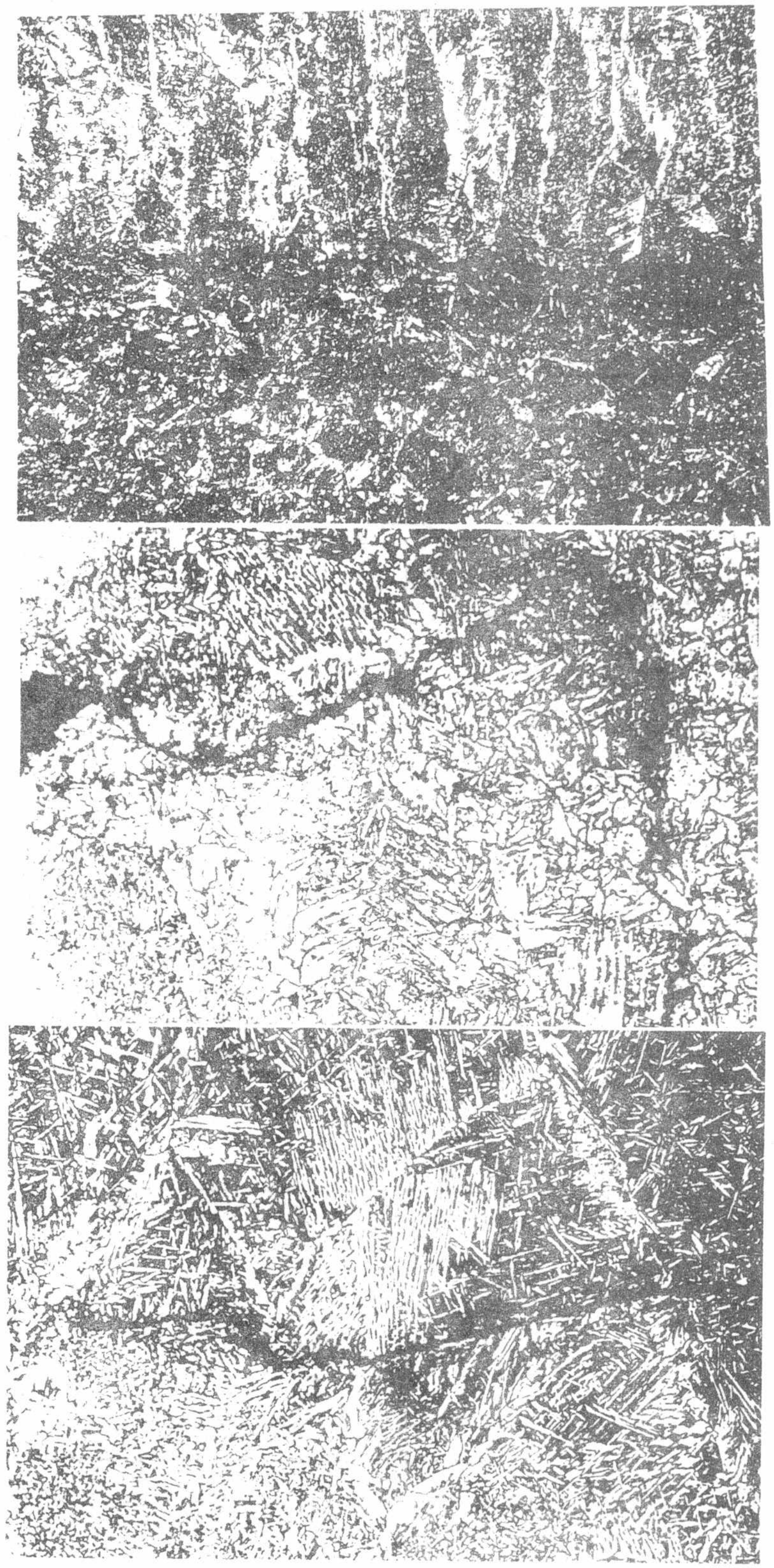



B) LEHIGH RESTRAINT SPECIMEN




C) CONTROLLED THERMAL SEVERITY (CTS) SPECIMEN

FIG.I. SCHEMATIC REPRESENTATION OF TEST SPECIMENS



A) NITAL ETCH 100 X

B) NITAL ETCH 200 X

C) NITAL ETCH 300 X

FIG.2. SOME EXAMPLES OF COLD CRACKS IN WELDED TEST SPECIMENS

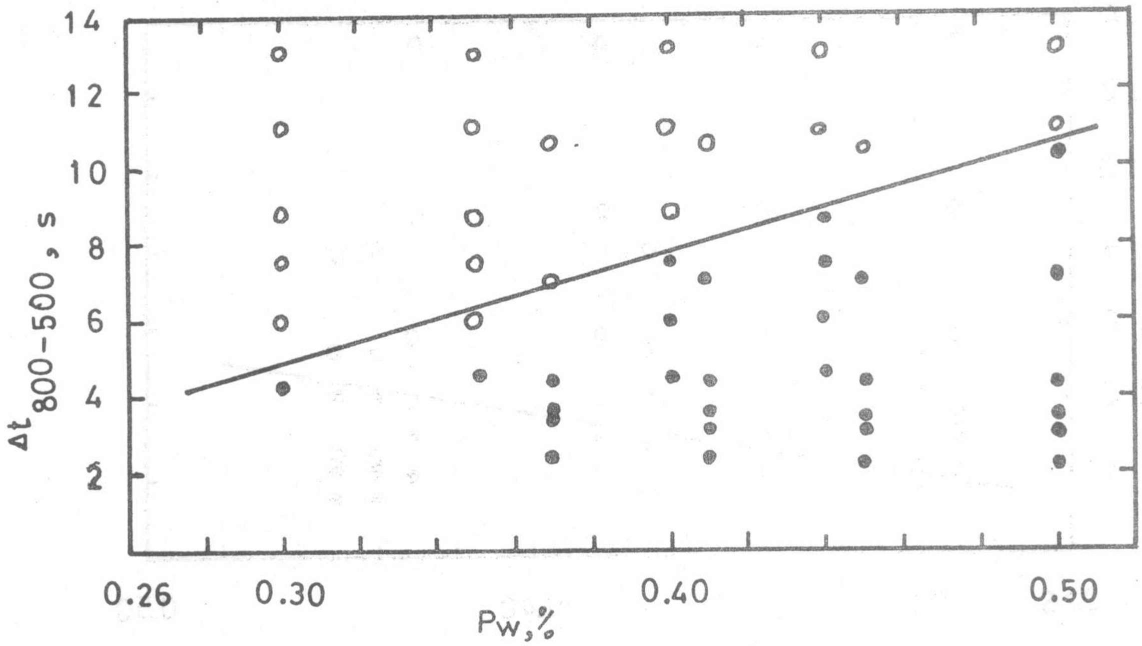



FIG.3. RELATION BETWEEN CRACKING PARAMETER $P_W$ AND $\Delta t_{800-500}$ IN TEKKEN TEST

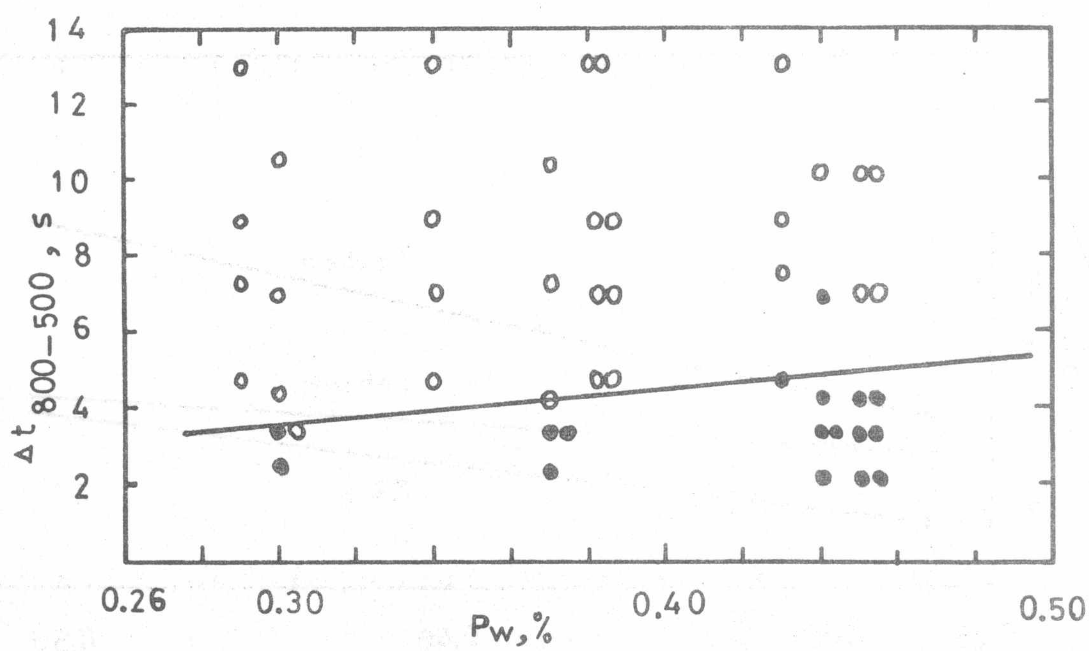



FIG.4. RELATION BETWEEN CRACKING PARAMETER $P_W$ AND $\Delta t_{800-500}$ IN LEHIGH TEST

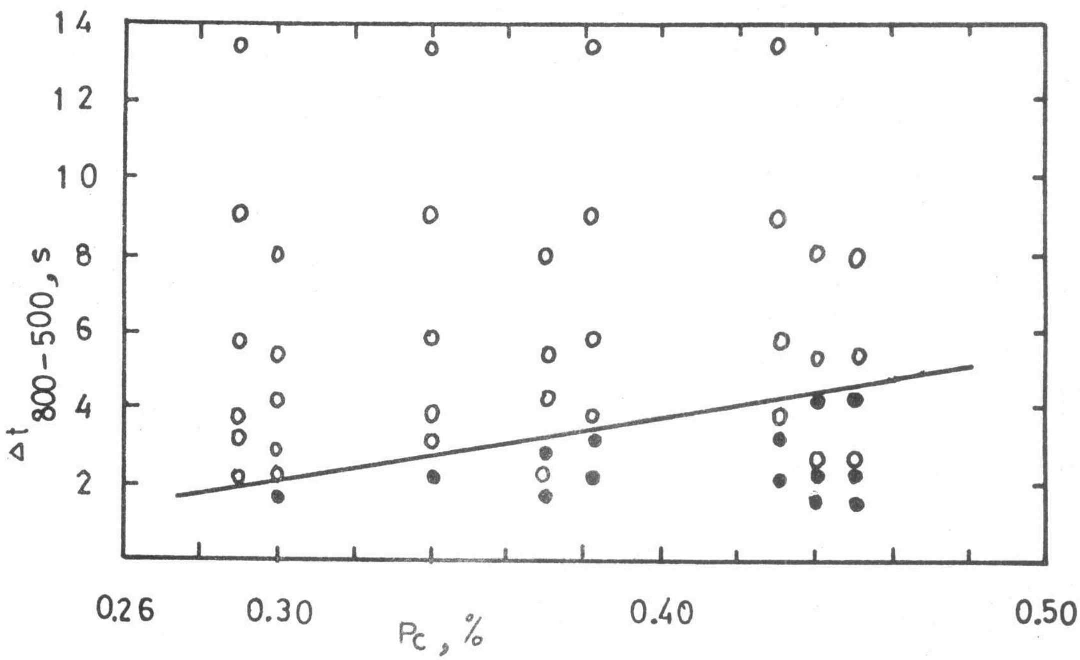



FIG.5. RELATION BETWEEN CRACKING PARAMETER $P_C$ AND $\Delta t_{800-500}$ IN CTS TEST

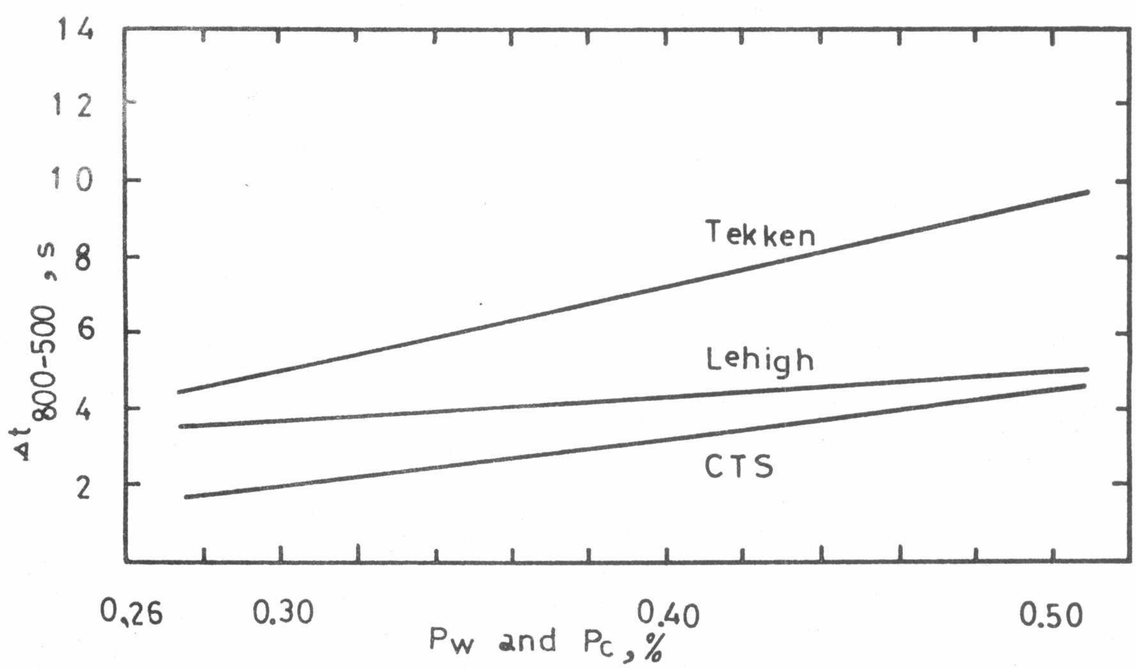



FIG.6. RELATION BETWEEN CRACKING PARAMETERS $P_W$, $P_C$ AND $\Delta t_{800-500}$ IN TEKKEN, LEHIGH AND CTS TESTS