STUDY OF DIMENSIONAL EFFECTS IN CONSTRAINED SHORT TENSION PLANE STRESS FRACTURE TOUGHNESS TESTS FOR POLYESTER FILM AND NEWSPRINT

By

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NOMENCLATURE

$2a_0$	Initial crack length
Δa	Half-crack extension
a_e	Effective half-crack size
B	Thickness of test specimen
2H	Height of test specimen
K_c	Plane stress fracture toughness
K_R	Crack growth resistance
K_G	Crack driving force
2W	Width of test specimen
σ_{gross}	Gross stress value in test specimen
CST	Constrained short tension
MD	Machine direction
CD	Cross direction

CHAPTER ONE

INTRODUCTION

1.1 Background and Motivation

This work is a continuation to a study by Buch [1]. In his study, test methods were reviewed and a recently developed constrained short tension (CST) test method was used to obtain the plane stress fracture toughness (K_c) for thin polyester films and paper.

This new CST test was developed because most existing in-plane fracture toughness tests for thin materials were complex and difficult to carry out. The method used by Buch uses a large, centrally notched specimen constrained between two grips. The specimen is placed in an electromechanical tension machine and crack growth and load data are taken. Fracture toughness values are then obtained from plotting K_R-curves and estimating K_c from these curves. One of the main advantages of the CST test is that anti-buckling plates are not necessary.

In CST tests, the width to height ratio (W/H) of the samples is important. It has been suggested that to perform the CST test and get consistent K_c values, W/H has to be greater than 5 [2]. Buch suggests that for narrow specimens with total widths equal to 4 to 6 inches, consistent K_c values can be obtained with $W/H \geq 4$. This criterion restricts specimens to a short height in most cases. For a six-inch wide specimen, the height cannot exceed 1.5 inches and still meet the above criteria. However, web handling applications can have heights, or lengths, over 100 feet long. Due to this length, an issue that is raised is how does K_c data obtained in a CST test for thin materials correlate to what is seen on a web line?

Web handling is the engineering science involved in the study of web transport through various processes. A web is a continuous, thin, and flexible material transported through various processes such as printing, drying, coating, and laminating before being converted to a final product [3]. The first part of this study utilizes a width to height ratio less than 4, and examines the effect it has on the K_c values of polyester films. This investigation will be carried out by performing tests using the facility developed by Buch and discussed in Chapter 3.

The second part of this study investigates, in a preliminary way, the fracture toughness of paper, specifically newsprint media. Due to the effects of temperature and humidity, tests run on newsprint medium must be done in a controlled environment to ensure reliable data. The very nature of paper makes it difficult to get reliable test data. Tests currently done on paper often employ tear methods, which do not effectively represent plane stress fracture toughness considerations. With the CST method, a first attempt at getting estimates on K_C values for newsprint media is made.

1.2 Objectives

The two main objectives in this study are:

1. To study the effect that a width-to-height ratio less than 4 has on the plane stress fracture toughness of a thin polyester film using a CST test method. Lengthening the test specimen and keeping the width and initial crack length constant allow the effect of decreasing the W/H ratio to be studied. By observing the K_c values when the

height of the specimen is increased, conditions seen on web handling lines may be foreseen and it can be estimated how fracture toughness is affected when long web spans are present. All specimens will be cut from the same stock material to ensure uniformity. Since the W/H ratio in this study will mainly be less than the W/H > 4 criterion, the results of these tests should be considered representative values only.

2. To obtain plane stress fracture toughness data for different specimens at various heights and initial crack lengths in newsprint medium. This will be a first attempt to apply the CST test to paper specimens. All newsprint is taken from the same stock material and cut to the specified dimensions.

CHAPTER 2

REVIEW OF LITERATURE

Relevant literature has been reviewed recently by Buch [1]. As of now, there are no current updates to report. Accordingly, only the key references in Buch's work that pertains to this study will be presented here.

2.1 Plane Stress Fracture Toughness Testing of Polymer Films

The most recent developments in the plane stress fracture toughness testing of polymer films are those by Buch [1]. In his study, he used a constrained short tension test to explore the geometrical and size constraints of polyester film coupons and the effects these constraints have on fracture toughness data.

In his work, Buch found that to obtain meaningful results using the CST test the following geometrical and size constraints are required:

1. $W > 4H$, where W is the half-width and H is the half-height.
2. $a_o > 0.8H$, where a_o is the initial half-crack length and H is the half-height.
3. Poisson's ratio for the test material must be in the 0.3 to 0.5 range.
4. $a_o = \frac{W}{3}$, where a_o is the initial half-crack length and W is the half-width.

The relevant conclusions from Buch's study are:

- The above specimen constraints eliminate buckling problems without the use of anti-buckling plates.

- The peak load values for polyester film specimens were found to be approximately 120% - 150% of the crack initiation load values.
- K_c for polyester film specimens decreases with increasing film thickness.
- K_c increases with increasing specimen width.
- For polyester films, it was found that consistent K_c values have been obtained with initial crack lengths that are half the size of the specimen width.
- Generally speaking, and increase is seen in K_c values with an increase in initial crack lengths up to $a_o = 2.0$ inches.
- Increasing the W/H ratio has a tendency to lower K_c. It was found that narrow test specimens, i.e. 6.0 inches, give consistent K_c values with $W/H \geq 4$.
- For the CST test geometry, specimen height is the limiting size factor.

The CST test method was recently developed by Tielking[4] for use on polyethylene films to obtain J_R-curves. Cotterell et. al. [2] used the findings of Tielking to apply the CST test method for testing thin materials that can be described by LEFM.

Cotterell found that to get valid K_C values $a > 0.8H$, $2a < W$ and, $W/H > 5$ constraints were applicable. With these conditions met, the following equation developed by finite element methods can be used to calculate the K_C value when the Poisson's ratio of a given material is in the range of 0.3 to 0.5:

$$K_C = \frac{\frac{P}{B(2W)}\sqrt{H(1-\nu^2)}}{C - a/W} \qquad \text{(2.1)}$$

where

P = applied load,

B = specimen thickness,

W = specimen half-width,

H = specimen half-height,

$a = a_o + \Delta a$, or initial half-crack length + crack extension

$\upsilon = 0.3$ to 0.5, and

$C = 1 + (0.3154 - 0.7666\upsilon^2)(H/W)$

The test method was tested on Kapton 300HN polyimide film and it was concluded that this method was suitable for measuring the fracture toughness, crack-growth resistance, fatigue and time-dependent crack-growth rates in thin materials from the results obtained in the study.

CHAPTER 3

TEST METHODOLOGY

3.1 Data Collection Plan

Data collection is divided up into two categories depending on the material being tested.

The first category outlines the collection plan for the tests that will be run using 48-gauge polyester film. All specimens have a width (2W) of 6 inches. The width of 6 inches is used because that is what the stock width of the roll is. This negates any flaws that could be introduced while cutting the width to size.

The initial crack length ($2a_o$) for each run is setup to be 1 inch. This value was determined from trial runs. Each run allowed a total of 1-inch total crack growth. Both of these values were used due to the findings of Buch and preliminary trial runs done in this study.

The length (2H) is varied from 0.8 inches to 30 inches. Thirty inches is the maximum length that can be tested using the Instron and fixture setup in this study. For each length, tests are conducted until five acceptable runs are obtained. Acceptable test runs are defined in Section 3.2.

The thickness (B) of the 48-gauge polyester film is 0.00048 inches. The thickness in webs usually does not vary much in the machine direction. The variation is usually on the order of 0.0001 to 0.0002 inches of change over 1000 feet of web length [5].

Therefore, due to the size of coupon specimens used in this study, the thickness can be considered constant.

During each run, the load and displacement data are recorded along with the crack growth data. These data are then used to estimate the K_C values for each run. Table 3.1 summarizes the collection plan for the 48 gauge polyester film runs.

Table 3.1: Data Collection Plan for 48 Gauge Polyester Film

Group Number	Test Runs	Specimen Height (2H)
1	10, 12, 13, 14, 15	0.8
2*	10, 12, 13, 14, 15	0.8
3	16, 17, 18, 21, 22	3.0
4	23, 28, 31, 33, 34	6.0
5	36, 37, 38, 40, 41	12.0
6	42, 45, 46, 48, 49	18.0
7	51, 54, 56, 57, 60	24.0
8	63, 64, 65, 68	30.0

Note: All Runs have $a_0 = 1.0$, $W = 6.0$

Group 2 data are identical to Group 1 data. However, the data are analyzed using K_R expression developed by Cotterell[2]. This will be discussed further in Chapter 4.

The second category outlines the collection plan for the tests run using newsprint media. All specimens have a width (2W) of 6 inches. The width of 6 inches was used because that was the maximum width of stock roll available.

Initial crack lengths range from 1 inch to 3 inches. Other initial crack lengths were investigated, but none gave acceptable load – crack growth data.

The thickness for the newsprint medium is 0.00028 inches. The variation in thickness is minimal, and similar to the variation stated earlier in the polyester webs, therefore it is considered to be constant also.

The length (2H) is varied from 2 inches to 3 inches. For each length, tests are conducted until four acceptable runs are obtained. During each run, the load and displacement data are recorded along with the crack growth data. These data are then used to estimate the K_C values for each run. Table 3.2 summarizes the collection plan for the newsprint media runs.

Table 3.2: Data Collection Plan for Newsprint Medium

Group Number	Test Runs	Specimen Height (2H)	Initial Crack Length ($2a_o$)
1p	p23, p27, p31, p35	2.0	2.0
2p *	p70, p74, p75	2.0	2.0
3p	p46, p49, p50, p54	2.0	1.0
4p	p37, p38, p39, p42	3.0	2.0
5p	p60, p64, p69	3.0	3.0

Note: All Runs have W = 6.0; * - crack initiated in machine direction of material

It should be noted that the size of these test specimens are under the W/H > 4 criterion. At the time this study was carried out, 6-inch wide newsprint media was all that was available. To fit into the range of acceptable W/H ratio, a height of 1.5 inches or less would have to be used. This was attempted in preliminary runs, but due to the nature of the test fixture no acceptable runs were completed. Therefore, it was decided to use the above numbers to at least get some representative K_c values using the test fixture created by Buch.

3.2 Defining Acceptable Test Runs

For a test run to be acceptable, there are several conditions that have to be met. First, there must be linear crack propagation. Linear crack propagation is achieved when the crack grows completely linear along the horizontal centerline of the specimen. Nonlinear propagation most often occurs when the specimen is mounted incorrectly in the grips.

Second, the crack growth rate must be equal on each side of the vertical centerline. It is possible for the crack to grow faster on one side or the other due to incorrect mounting of the specimen initially. This can also occur if the initial crack is not cut sharply, or if the initial crack is not cut equally on each half of the vertical centerline. Actions taken to prevent both scenarios are discussed in Section 3.4.

3.3 Development of CST Test Grip Fixture

One of the most essential components needed to carry out the CST test is the test grip fixture. For this study, the fixture used was the one designed and manufactured by Buch[1]. In designing the fixture, three requirements are used for development. These requirements are:

1) The grips must have faces that prevent the materials from slipping and the material should not deform under load.
2) The grips must have sufficient bending stiffness so that the deflection of the grips under load is minimal.
3) Ease of specimen preparation:

- Specimens of different height, width, and thickness should be tested without major modifications.
- Quick and easy gage length setting and center crack location.

The fixture designed and manufactured by Buch to meet these criteria is shown in Figure 3.1.

Grip Plates

The grip plates (Fig. 3.1 – 1) are made of steel and can test a specimen with a maximum width of 12 inches and a minimum width of 4 inches. The plates are faced with a rubber gasket 0.09 inches thick. The gaskets are glued to the machined surfaces with contact cement. One addition made is placing markings on the rubber gasket to insure proper alignment of the test specimens. A line was place on each gasket to mark the vertical centerline. Also marks were placed on each gasket that would allow alignment horizontally. These marks correspond to marks placed on the test specimens upper and lower, left and right corners.

C-type Fixtures

The upper and lower C-type fixtures (Fig. 3.1 – 2) are made of steel and are connected to the load cell and the Instron surface, respectively, by a pin. The bolts located in the back of the fixture are for support and location of the grip plates. The bolts located in the front provide the clamping force on the grip plates.

Holding Plates

The holding plates (Fig. 3.1 – 3) are made of aluminum (6061-T6). Holes are drilled in the plates to match the specimen heights up to 4 inches. These plates provide support of the specimen when loading it into the test fixture on the Instron. Due to the nature of the testing done with polyester films, additional holding plates had to be manufactured for each corresponding length. These plates were made from ½" square tubing and cut to the appropriate length.

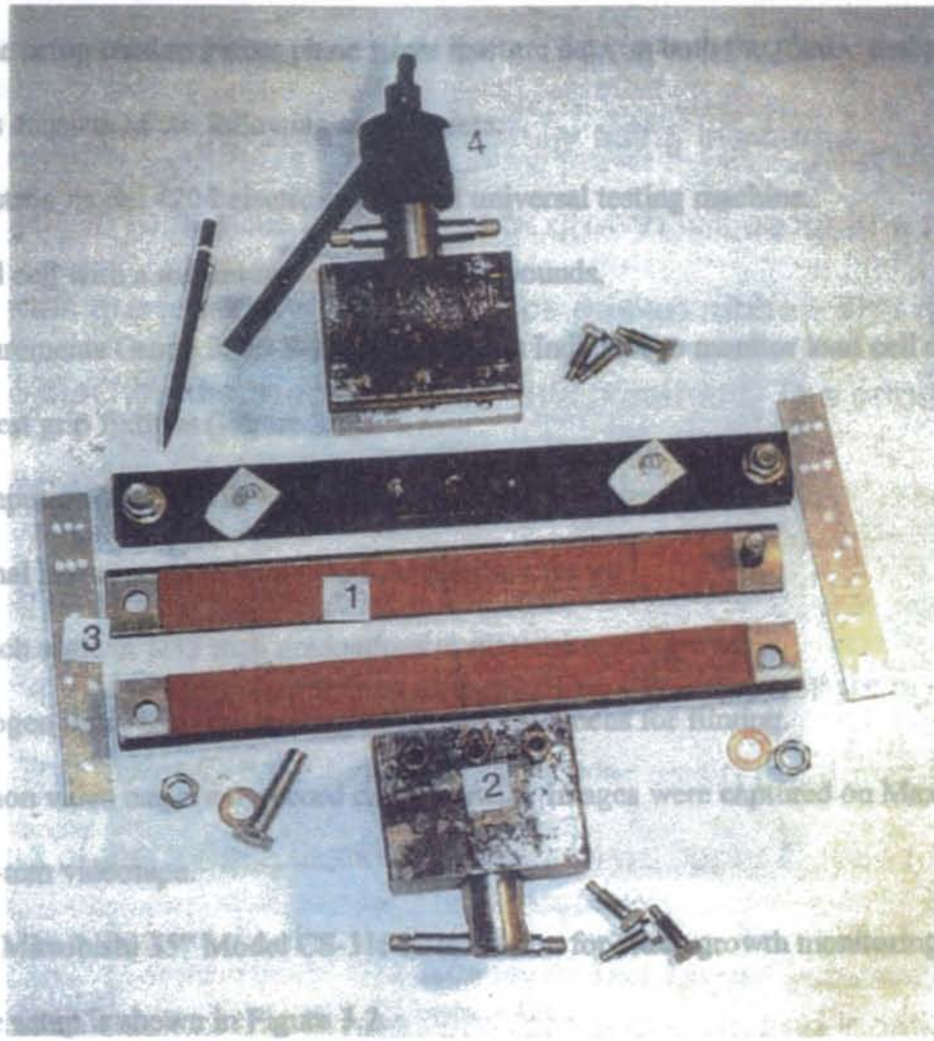

Figure 3.1: CST Test Grip Fixtures [1]

1. Grip plate with gasket rubber faces
2. C-type fixtures
3. Holding plates
4. Instron load cell connector

3.4 Testing Apparatus

The setup used to gather plane stress fracture data on both the plastic and paper specimens consists of the following components:

(1) An Instron model 4204 electromechanical universal testing machine.

(2) A load cell with a maximum capacity of 100 pounds.

(3) Measurements Group 3800 Wide Range Strain Indicator to monitor load cell data.

(4) CST test grip fixtures (Figure 3.1).

(5) A computer with LabView data analysis program.

(6) National Instruments SCB-68 Data Acquisition Board

(7) A 6 inch scale in 1/32 inch graduations to measure crack growth.

(8) A halogen light, used for lighting of the test specimens for filming.

(9) A Canon video camera to record crack growth. Images were captured on Maxell GX-MP 8-mm videotape.

(10) A Mitsubishi 35" Model CS-31301 television for crack growth monitoring.

The entire setup is shown in Figure 3.2.

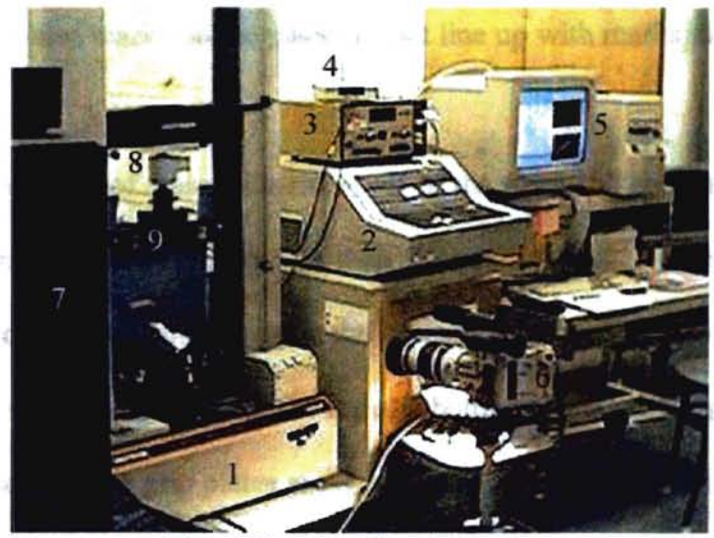

Figure 3.2: Testing Apparatus

1. Instron model 4202 electromechanical universal testing machine
2. Control console for Instron 4202
3. Measurements Group 3800 Wide Range Strain Indicator
4. National Instruments SCB-68 Data Acquisition Board
5. Computer with LabView data analysis program
6. Canon video camera
7. Magnavox television
8. A 100 lb. load cell
9. CST test grip fixtures

3.5 Specimen Preparation and Test Procedure

Specimen Preparation

Specimen preparation for both plastic and newsprint is similar. To ensure the proper size, cardboard placards are made for each height. The placards have horizontal and vertical centerlines marked on them, along with marks indicating various initial crack lengths. There are also marks on the placards that line up with marks placed on the grip plates.

Initially, a length of material is rolled off of the stock roll and cut to the correct height using the placard. The specimen is then placed on the placard. Marks are then drawn on the specimen that correspond to the horizontal centerline as wide as the initial crack length, the vertical centerline at the top and bottom edges of the specimen, and the lines that correspond to the grip plates at the right and left edges of the specimen. These marks, with the exception of the horizontal crack length mark, are placed on the plastic specimens using a black Sharpie® fine point marker. The horizontal crack length mark is placed on the plastic specimen using a red Sharpie® fine point marker. The red ink allows the crack growth to be seen more clearly on the video camera. The marks are placed on the newsprint specimens using a ball point pen. For the newsprint specimens, only the grip plate lines and the vertical centerline are marked.

After the marks are made on the specimens, the crack is introduced using an Exacto knife. The specimen is sliced down the horizontal centerline using a ruler to ensure a straight cut. Marks on the placards indicate how long the initial crack lengths need to be according to the test run being performed.

Test Procedure

- After the test specimen is marked appropriately, it is placed on the grip plates and the corresponding marks are lined up. To aid in this line up process, the correct gap distance between the upper and lower grip plates is measured using a set of dial calipers; a framing square is used to ensure that the plates are in-line. Once the specimen is oriented correctly on the grip plate, the opposing grip plate is place on top of the specimen and the bolts are hand tightened.
- Next, the holding plates, shown in Figure 3.1, are placed over the dow pins that protrude out of the grip plate surface. These holding plates are to keep the specimen from being pre-stressed while loading it in the Instron. The plates shown are good for runs up to six inches in height. Other holding plates were designed to account for the longer height value test runs. Once the holding plates are in place, the grip plate bolts are then tightened using a ¾" box end wrench. This setup is shown in Figure 3.3.
- The specimen is then taken to the Instron and placed on a spring seat while the crosshead is lowered down and the top grip plate is lined up in the upper C-type fixture as shown in Figure 3.4. The six hex head bolts are then tightened using an allen wrench. The spring seat allows for easy alignment of the holes and the bolts in the grip plate and the C-type fixture.

Now, the spring seat is removed and the bottom grip plate is lowered down into the bottom C-type fixture and the grip plate holes and C-type fixture bolts are lined up. At this time, the bottom grip plate is sitting in the C-type fixture and the holding plates are removed. The hex head bolts can be tightened accordingly. Care must be taken here to ensure that no preload is introduced into the specimen when tightening the bolts.

- The crosshead of the Instron is then moved upward just enough to place a preload in the specimen. For the polyester test runs, a preload value of 5 lbs. is used. In comparison, the crack initiation loads are approximately 18 lbs. For the newsprint test runs, a preload value of 4 lbs. is used. Due to the difficulty in seeing exactly when the crack growth starts in newsprint, the crack initiation load cannot be determined. However, in the rolled direction of the newsprint the maximum load seen is approximately 50 lbs. in the (6x1x2) and (6x2x2) specimens, and 35 lbs. in the (6x3x2) and (6x3x3) specimens.
- At this time, a 1/32nd scale is placed just at the bottom edge of the initial crack and centered appropriately. The halogen light is then setup to give the maximum viewability. This is achieved by looking at the TV screen, which is setup to show the view as seen through the video camera. Next, the video camera is positioned to ensure that the whole crack growth will be captured. In every case, whether polyester or newsprint, the total crack growth is limited to one inch. Also, at this stage, the Labview program is reset and prepared for the test run to begin.
- With all of the above accomplished, the test run is now ready to begin. To start the run, the crosshead displacement button is depressed on the Instron and the record button is depressed on the video camera. These two buttons are depressed simultaneously. The test is allowed to run until one inch of crack growth is achieved, then the crosshead is stopped, the video camera is shut off, and the Labview program is terminated.

This procedure is repeated until all of the desired test runs have been made. The crosshead displacement for the polyester runs is .04 inch/min., as established by Buch. The maximized crosshead speed for the newsprint runs is .02 inch/min. The speed of .04 inch/min. is too quick to get accurate data for the newsprint material with the current method. Namely, once the crack initiation occurs, the crack grows very rapidly. This rapid growth is too fast to get crack growth data via the video capturing method used in this study. The .02 inch/min. setting allows for slower crack growth that can be captured using the method presented here.

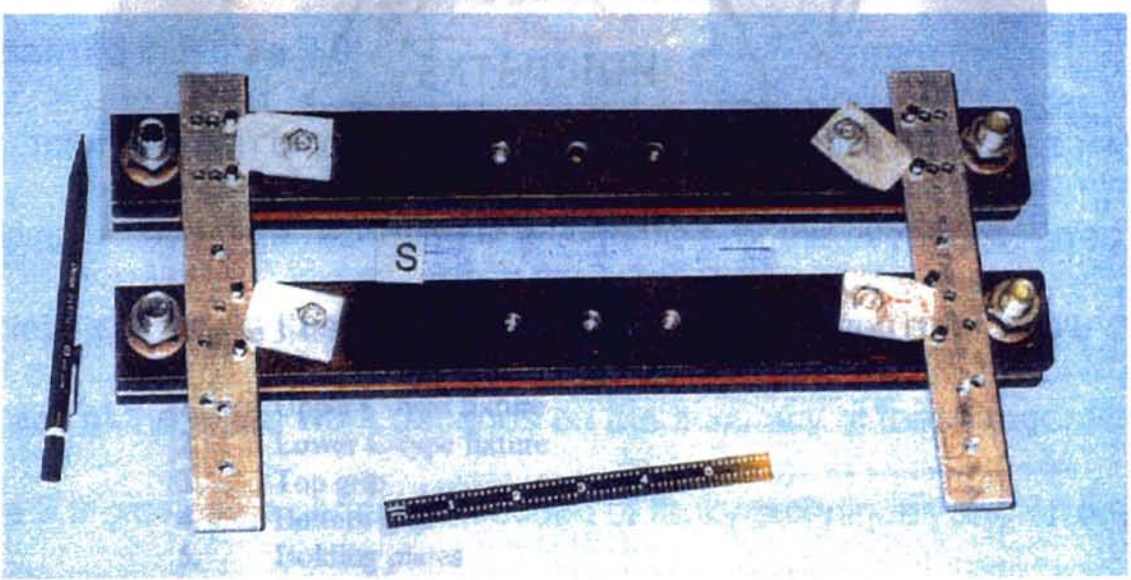

Figure 3.3: Specimen shown in grip fixtures with holding plates in place [1].
48 gauge polyester film.

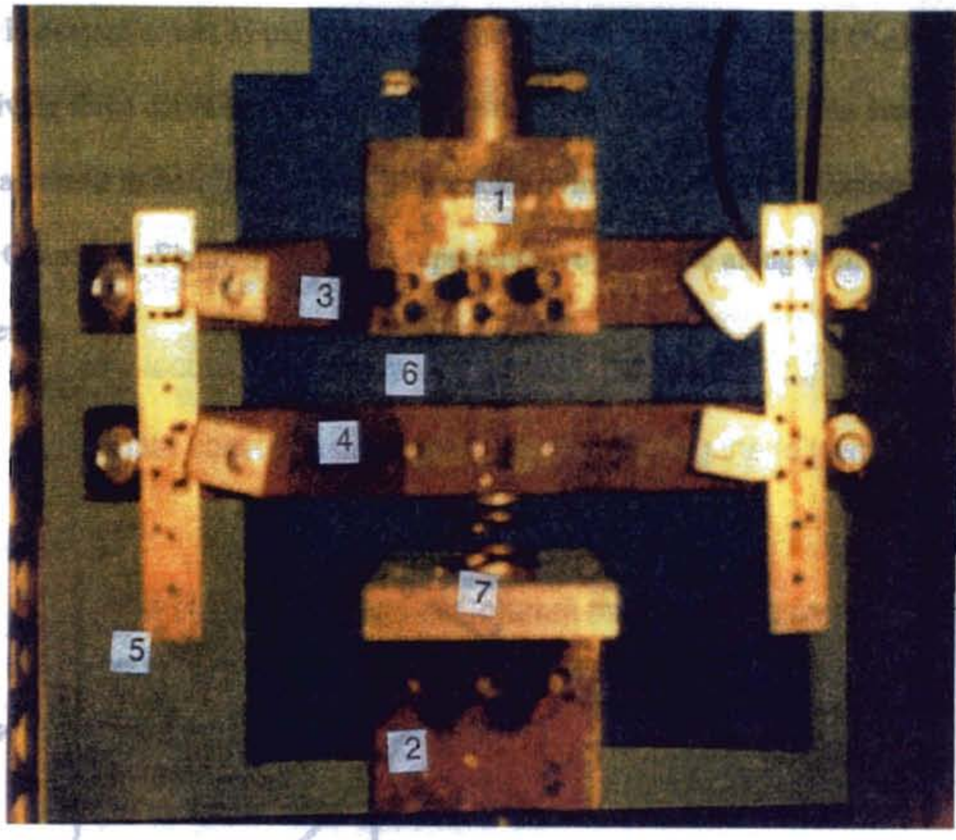

Figure 3.4: Spring seat arrangement for test grip fixture [1].

1. Upper C-type fixture
2. Lower C-type fixture
3. Top grip
4. Bottom grip
5. Holding plates
6. 48 gauge polyester film
7. Spring seat arrangement

3.6 Estimation of K_C Values

The estimation of K_C values for this study is done using K_R curves. A K_R curve is a plot of the crack growth resistance as a function of the effective crack extension, Δa. Another important aspect of the K_R curve is the crack driving force curve (K_G) [6]. The crack driving force curve is discussed in more detail in Chapter 4. For this study, the K_G curve is assumed to be a linear curve. The crack driving force curve is discussed in more detail in Chapter 4. Figure 3.5 shows a representative K_R curve along with its various components.

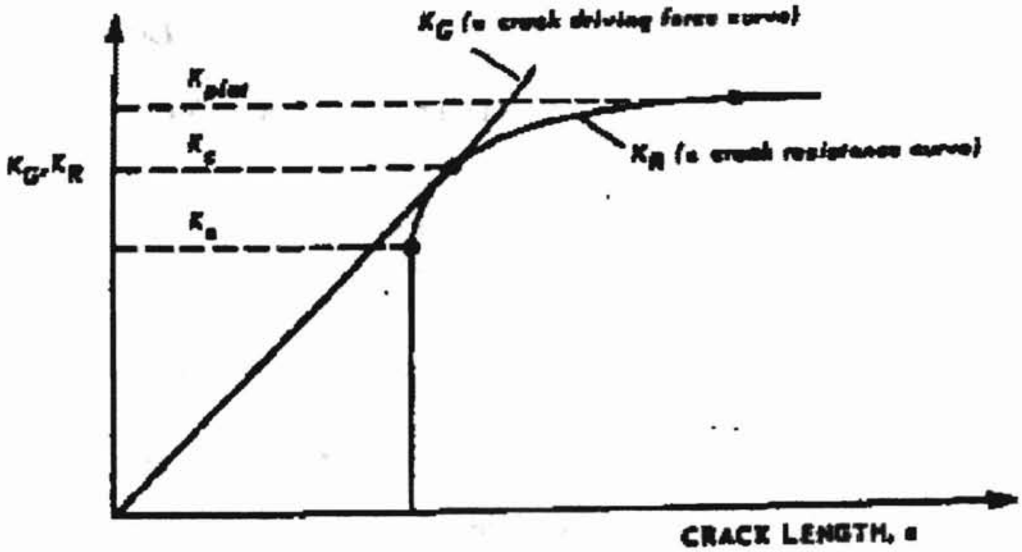

Figure 3.5: Representative K_R curve [6].

The important features in Figure 3.5 are the K_R curve, the K_G curve and the point K_C. As shown by the figure, K_C is the tangency point (K_G, K_R). The K_o and K_{plat} values will be ignored for this study, since the focus is on the comparison of plane stress fracture toughness values on different specimens.

To obtain a K_R curve, the following data are needed.

- The load at a given instance.
- The width and thickness of the test specimen
- The crack growth data.

For center cracked test specimens, the following expression represents the K_R value:

$$K_R = \frac{P}{WB} \cdot \left[\pi a \cdot \sec\left(\frac{\pi a}{W}\right)\right]^{\frac{1}{2}} \quad [7] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

where:

P = applied load
B = specimen thickness
W = total specimen width
a = the effective half crack size ($a_o + \Delta a + r_Y$)
where
a_o = the initial half-crack length
Δa = the half-crack extension
r_Y = the plastic zone size correction

3.7 Obtaining Load-Time Records

Data are gathered for both the polyester and the newsprint tests in a similar manner. The load and crosshead displacement data from the Instron are recorded and saved onto a PC equipped with LabView data acquisition software. To correlate these data to the crack growth data captured by the video camera, it is necessary to convert the displacement of the crosshead into a time-based format, specifically seconds. This conversion is done with the knowledge of the crosshead displacement rate that was given in Section 3.4 for each material. After this conversion, load versus time plots are made.

3.8 Crack Growth Measurements

The crack growth is measured using a 1/32nd –inch scale and is recorded using a video camera. To get the crack growth data, the video is played back in slow motion and the crack growth data are recorded at various time intervals. The advantage of this method over the projection method used by Buch is that it allows the measurements to be taken in one frame of reference, since the scale is in place already on the video.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Using K_R-Curves to Estimate K_c Values

With the load-time records and the crack growth-time records, the load and crack growth data can be correlated. The K_R curves created in this study are constructed using Equation 3.1 due to the fact that fewer validity constraints are placed on this expression. However, for the polyester specimens that have a height of 0.8 inches, K_R curves are also constructed using Equation 2.1. The reason Equation 2.1 is not used exclusively in this study is because of the criterion established by Cotterell et. al. [2] stating that $a_o > 0.8H$. The only instance this constraint is met is for the polyester runs with 2H = 0.8. For this case, the a_o of 0.5 is greater than 0.8 H (where H = 0.4). These runs make up the Group 2 data set shown in Table 3.1. The K_R curves corresponding to these runs are shown in Figure 4.2 and are discussed more thoroughly in Section 4.2.

For this study, the crack driving force ($K_G = f(P, \sqrt{a}, \frac{a}{W})$ [6]) curve was taken to be linear. Most likely, the K_G curve is parabolically shaped in some manner. However, since the scope of this study is exploratory and comparative, the linear assumption will suffice. It should be noted that the linear assumption would likely cause the actual K_C values to be somewhat lower than the values obtained in this study. The K_G curve is a geometrically constructed line passing through the points (a_0, 0) and (K_G, K_R), with the latter point being the tangency point of the K_G and K_R curves. The tangency point's location is determined graphically from the geometrically constructed K_G curve and the point where it comes in contact with the K_R curve. This contact point is determined in Microsoft Excel 97® by zooming in on the plot with a magnification of 200%. The tangency point is then estimated and a horizontal line is drawn from the point of tangency to the K_R (vertical) axis. The outcome of this line on the K_R axis gives the corresponding K_C value. Since the tangency point is a graphical estimation, there is the possibility of having a spread in the K_c values depending on where the actual tangency point occurs. It is estimated that graphically determining the tangency point in the manner incorporated in this study could result in a spread of approximately 0.2 – 0.4 (ksi)in$^{1/2}$ for the K_C values.

The K_R curves for the polyester specimens are shown in Figures 4.1 – 4.8. Following these figures is a section of summary and discussion for the polyester runs. Figures 4.11 – 4.15 show the K_R curves for the newsprint runs. Following these figures is a section of summary and discussion for the newsprint runs

Figure 4.1: K_R curves for Group 1 test runs

Group 1: Test Runs 10,12, 13, 14, 15

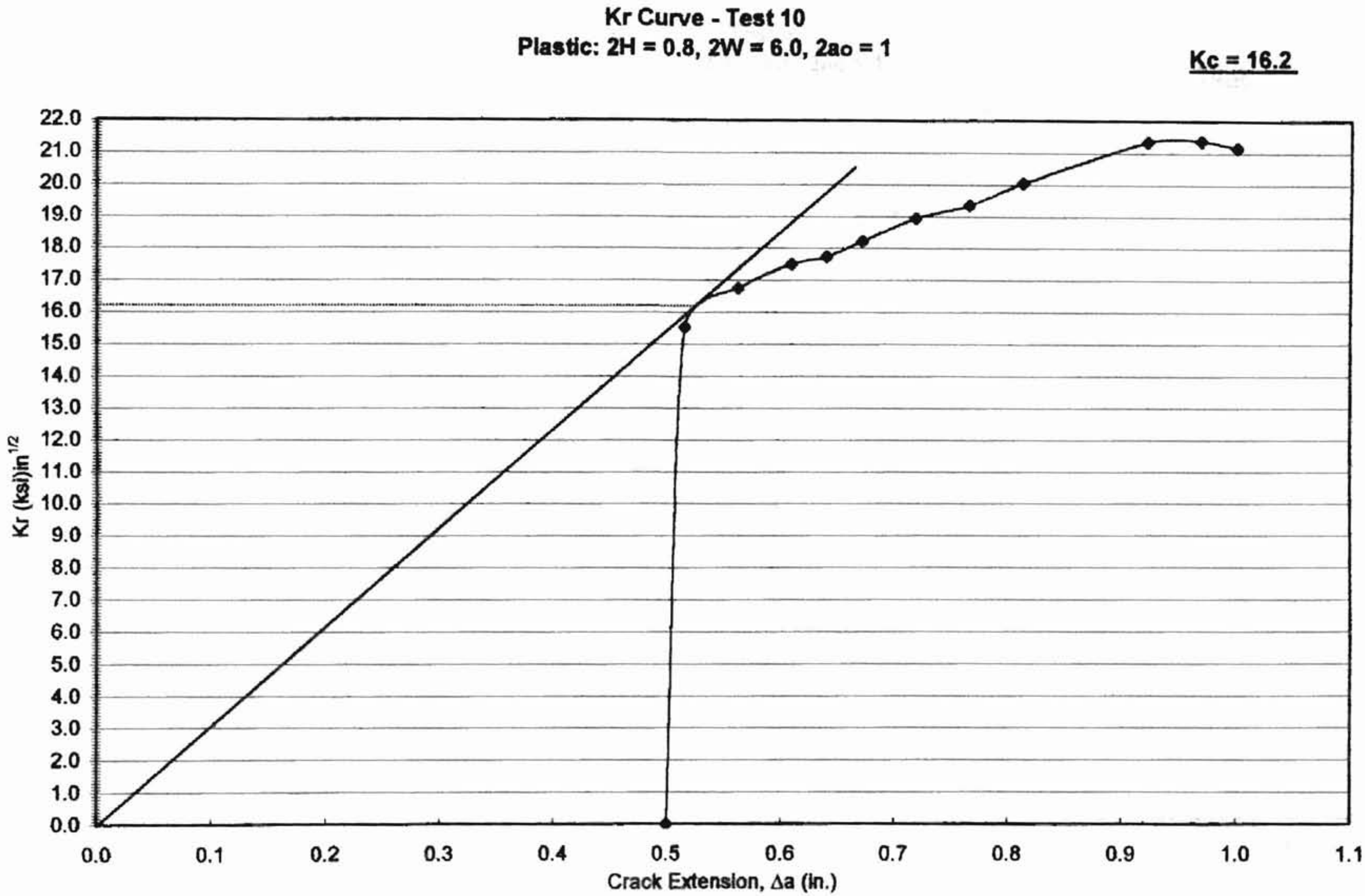

Figure 4.1.1: K_R Curve for Test 10 data

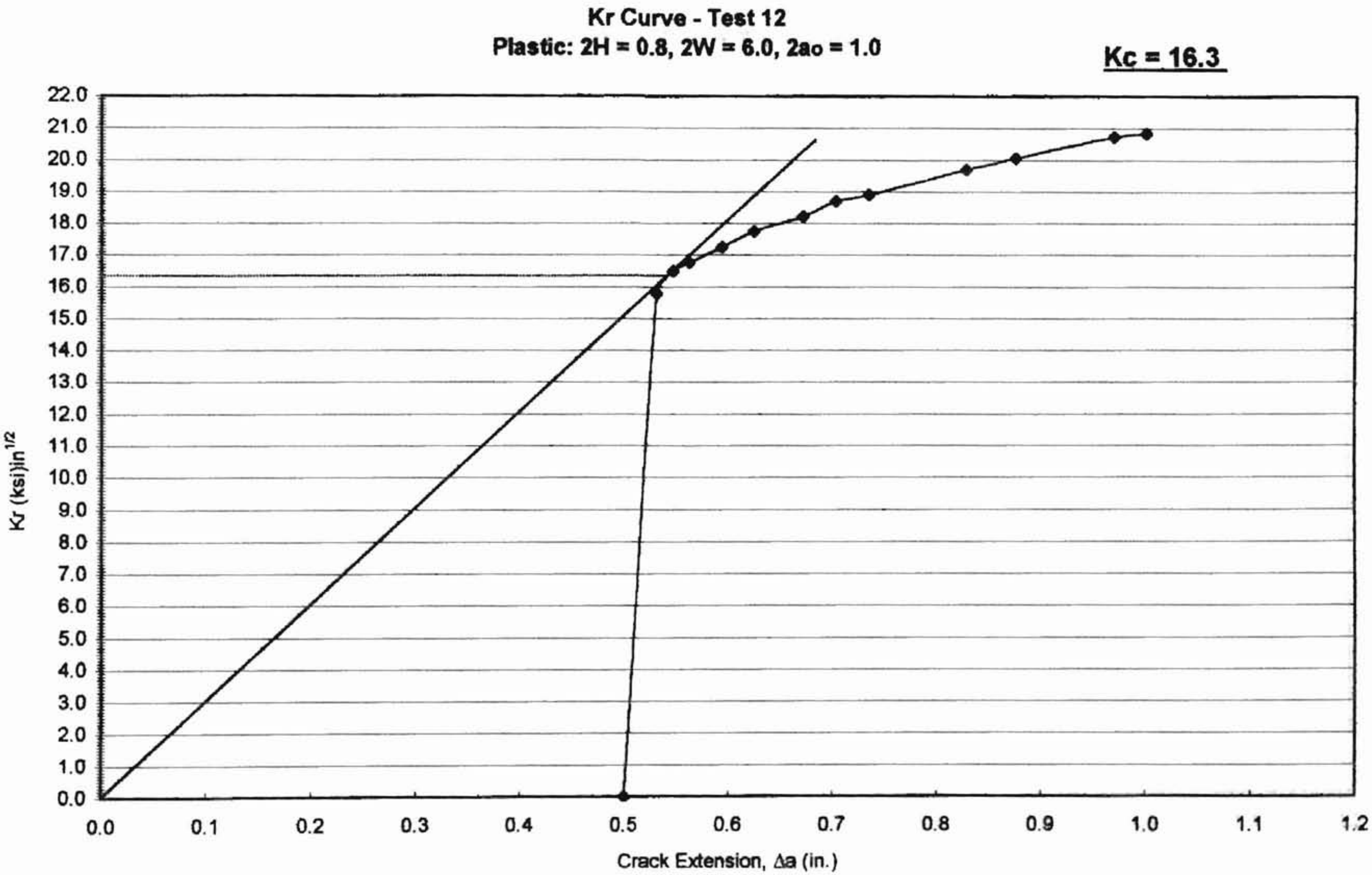

Figure 4.1.2: K_R Curve for Test 12 data

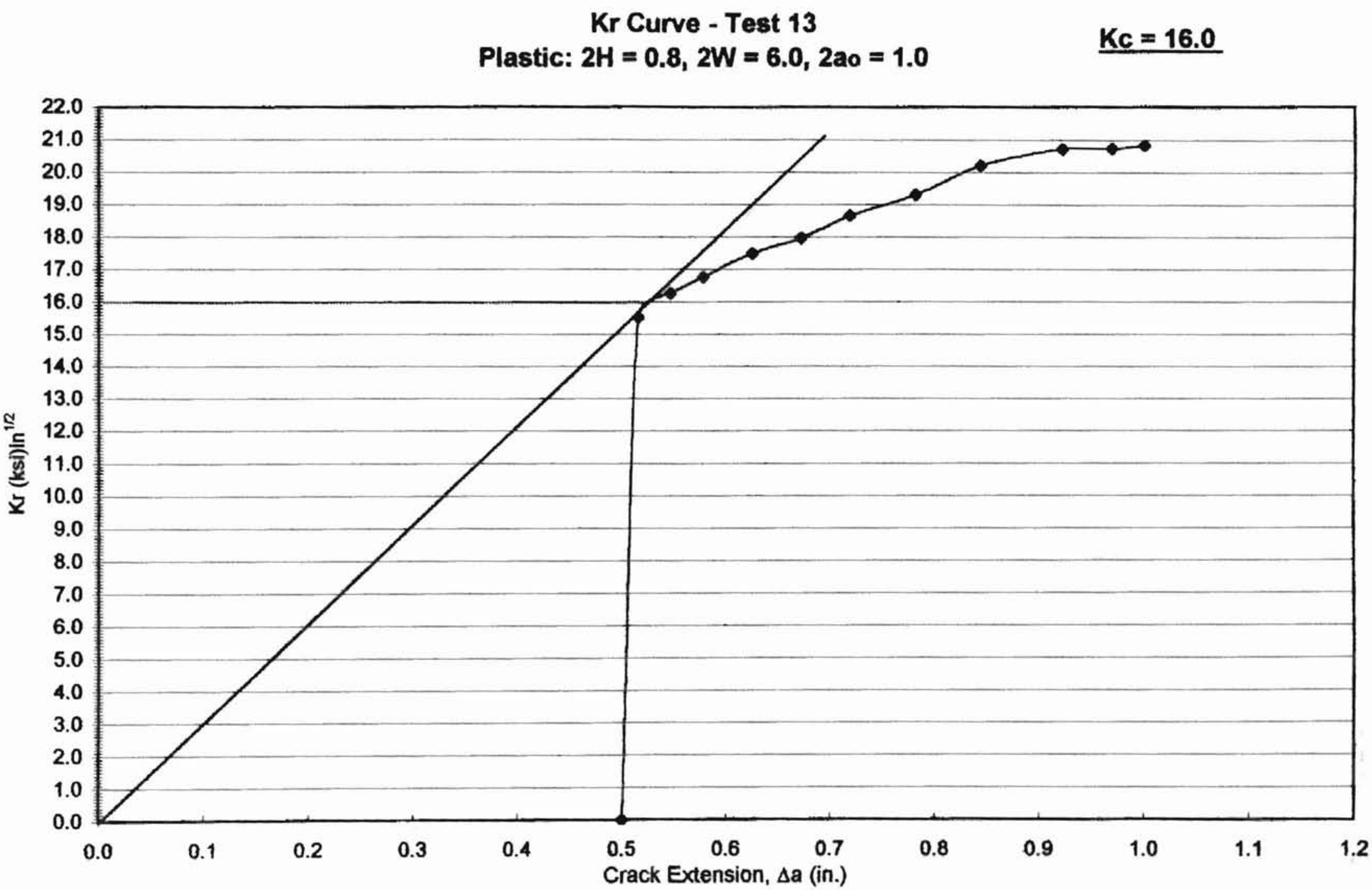

Figure 4.1.3: K_R curve for Test 13 data

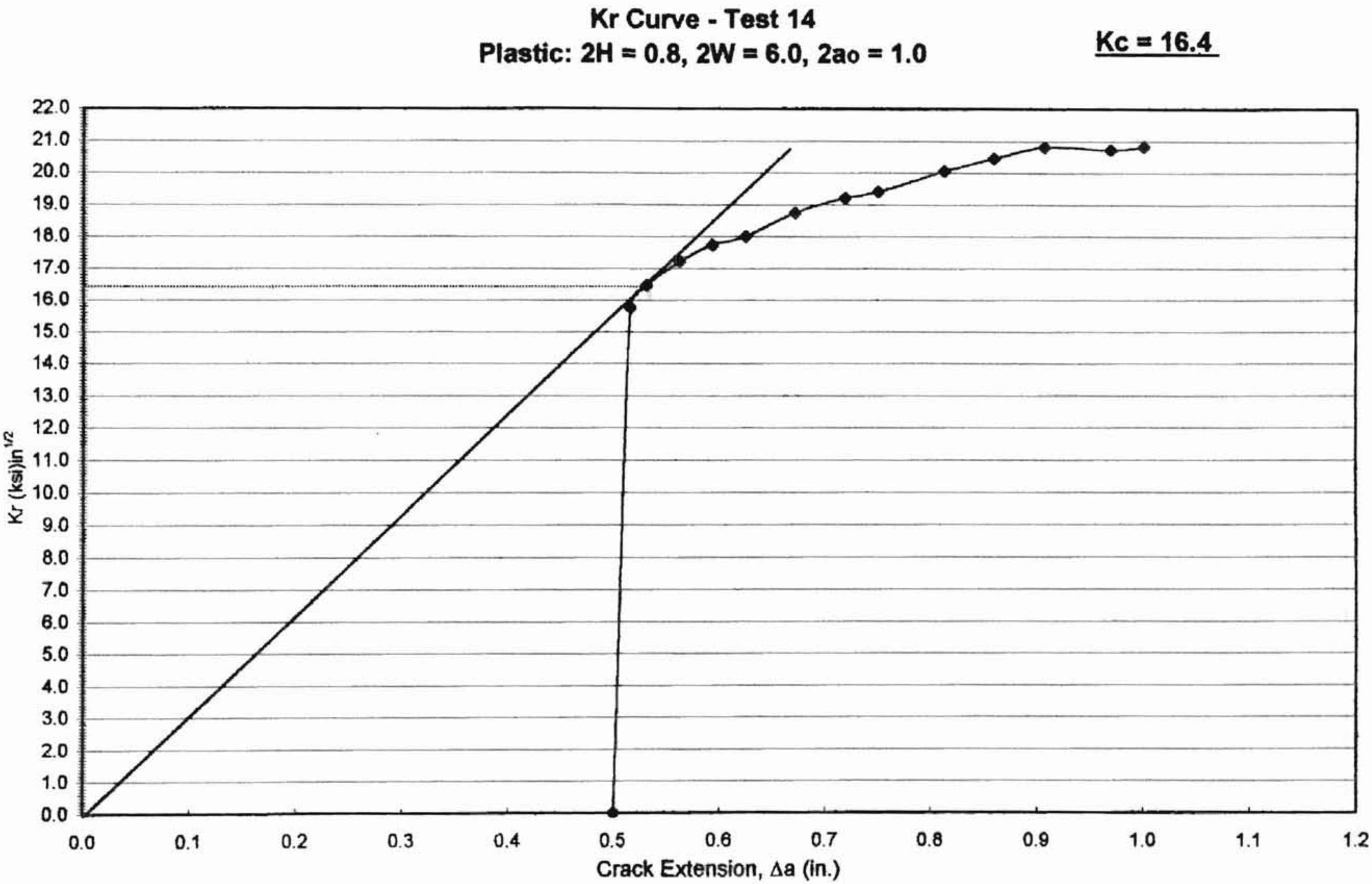

Figure 4.1.4: K_R curve for Test 14 data

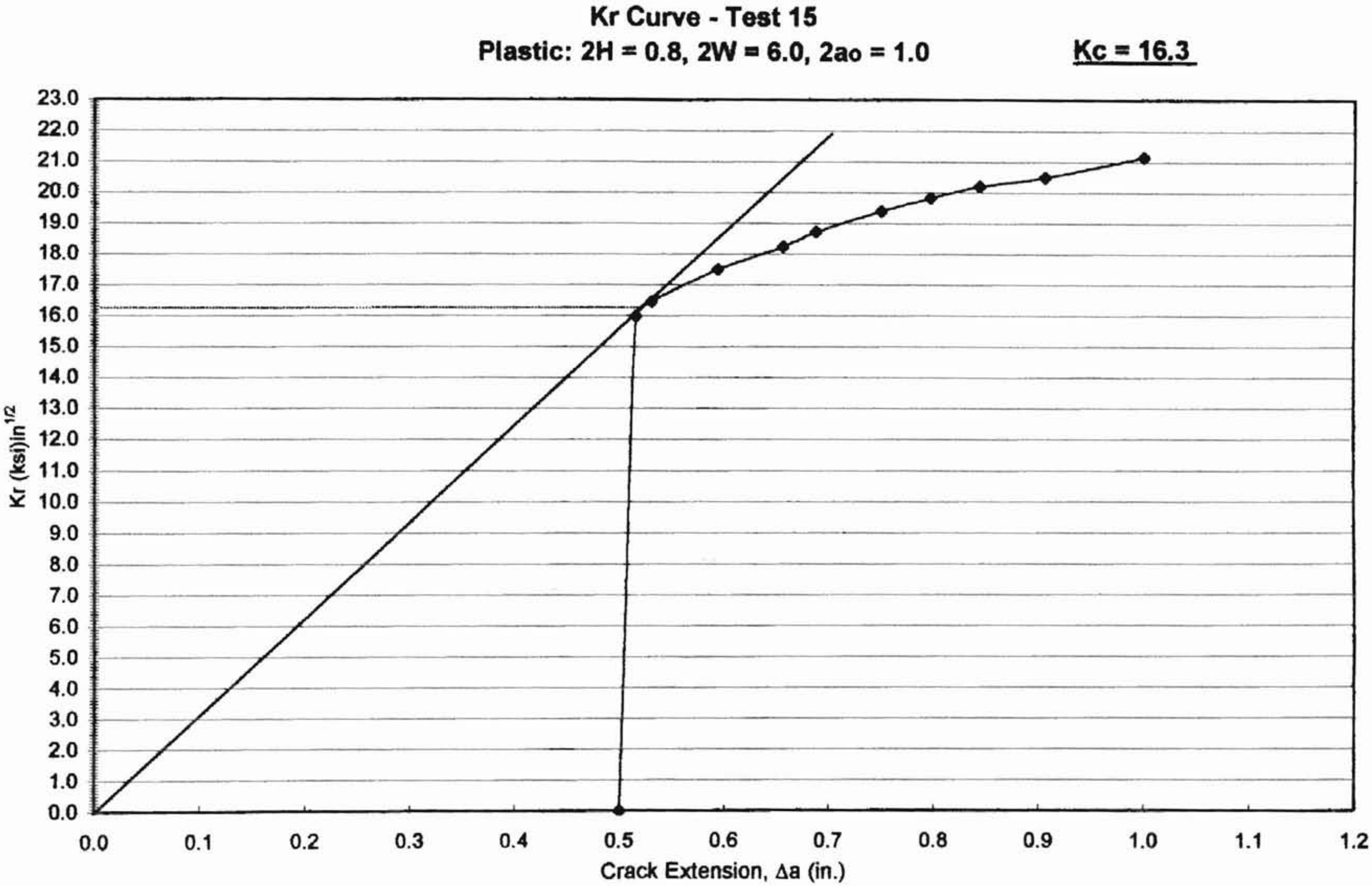

Figure 4.1.5: K_R curve for Test 15 data

Figure 4.2: K_R curves for Group 1 test runs using Cotterell Expression

Group 1: Test Runs 10,12, 13, 14, 15

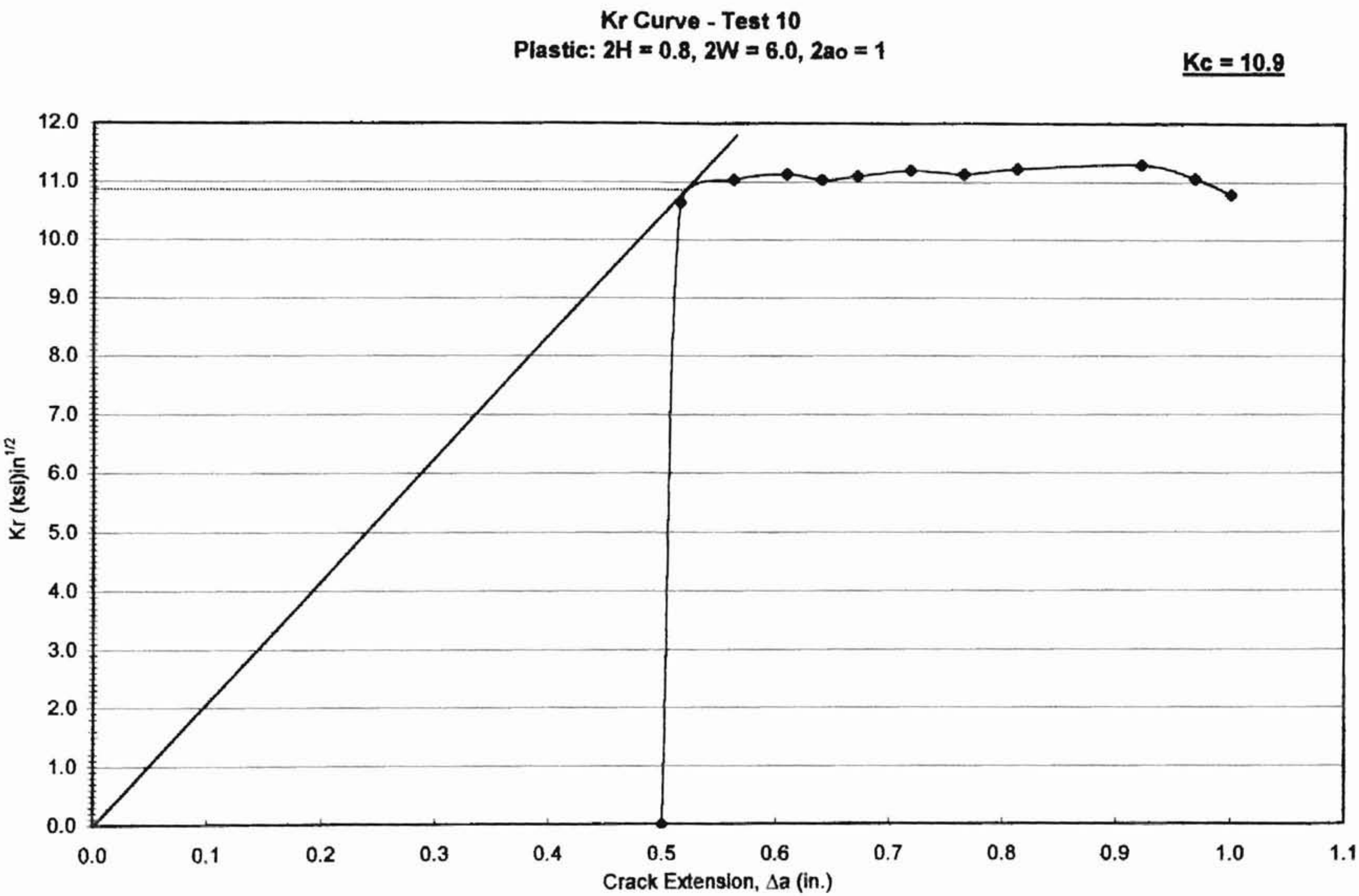

Figure 4.2.1: K_R Curve for Test 10 data (Cotterell)

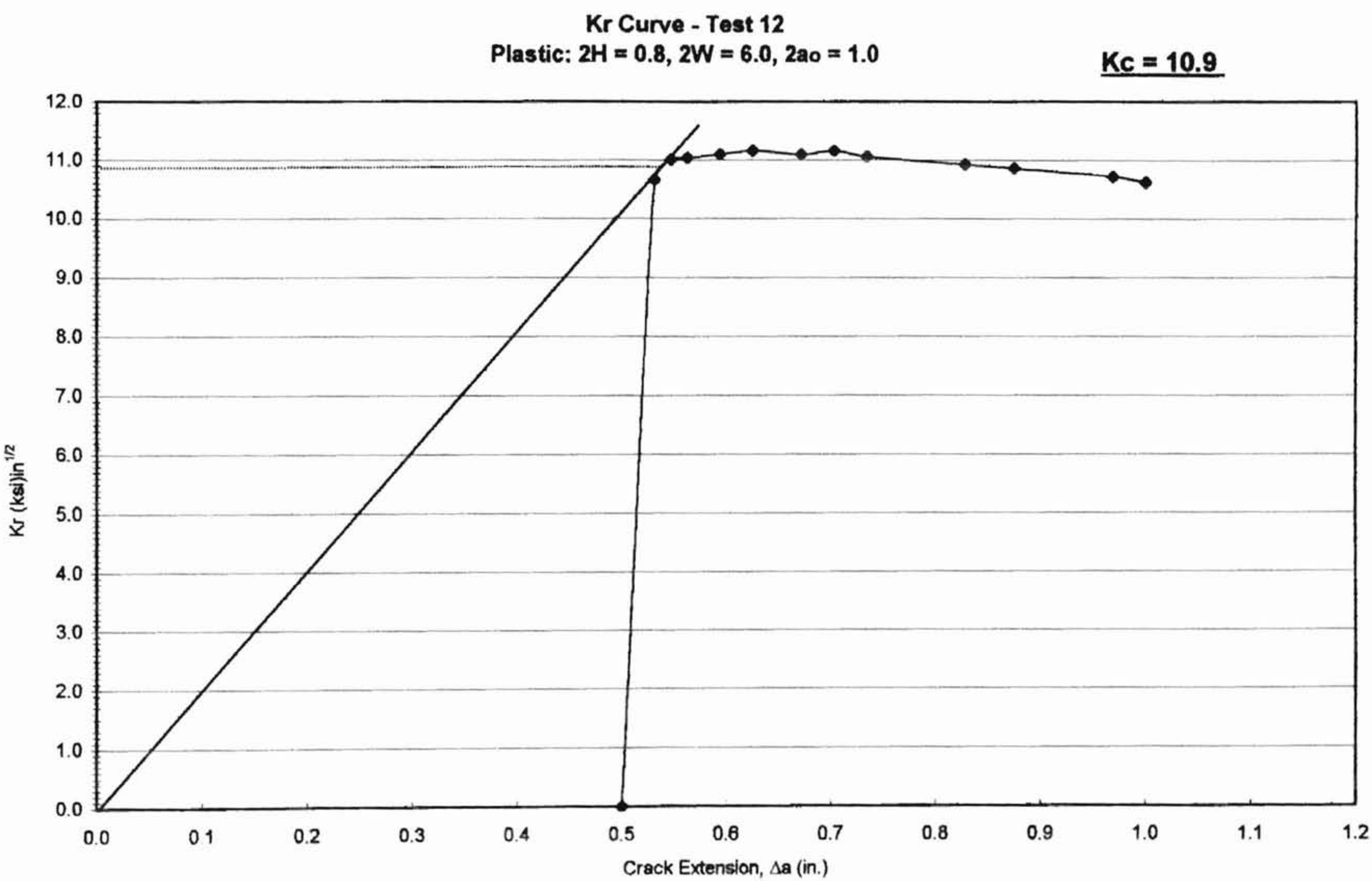

Figure 4.2.2: K_R Curve for Test 12 data (Cotterell)

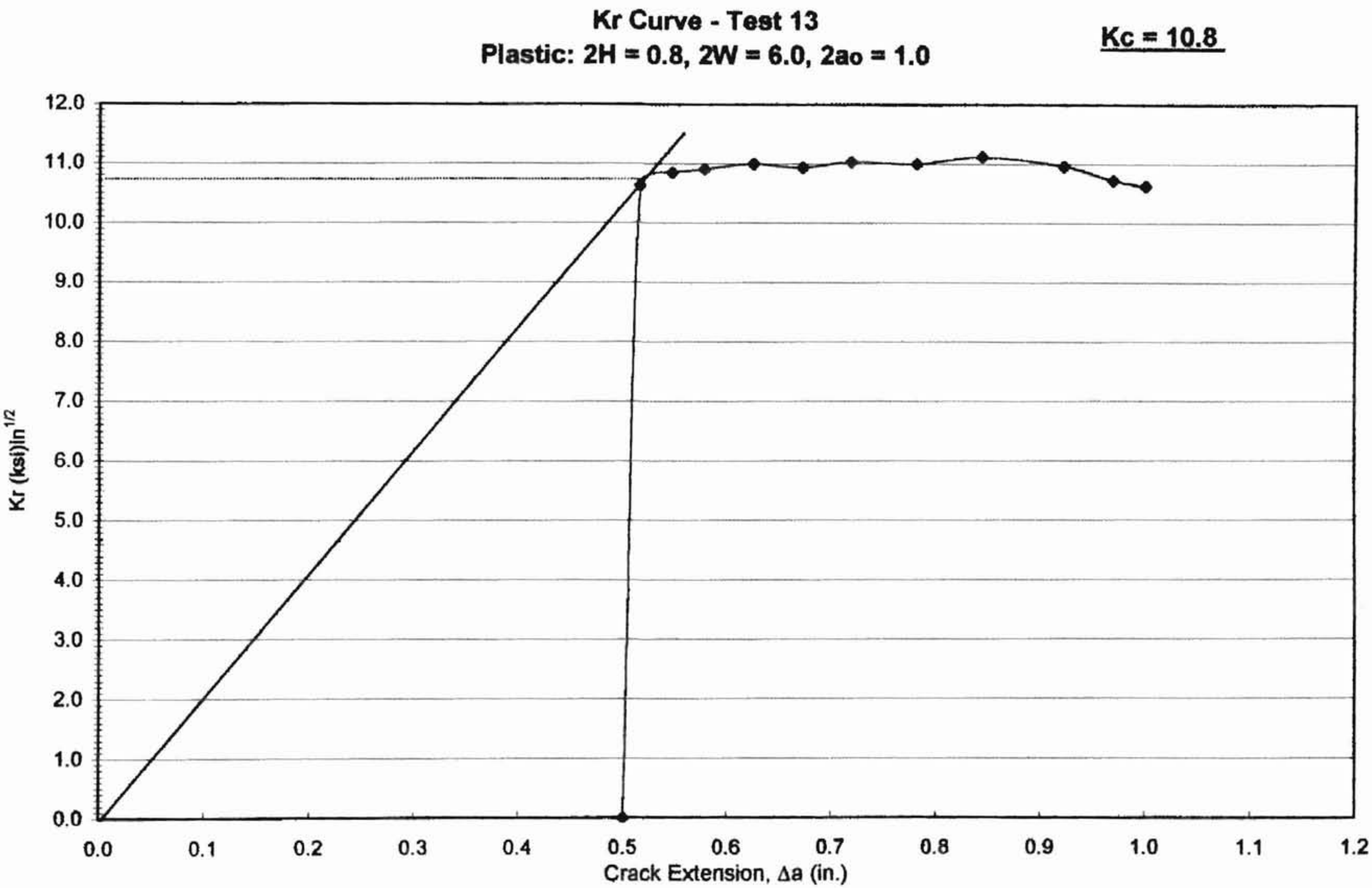

Figure 4.2.3: K_R Curve for Test 13 data (Cotterell)

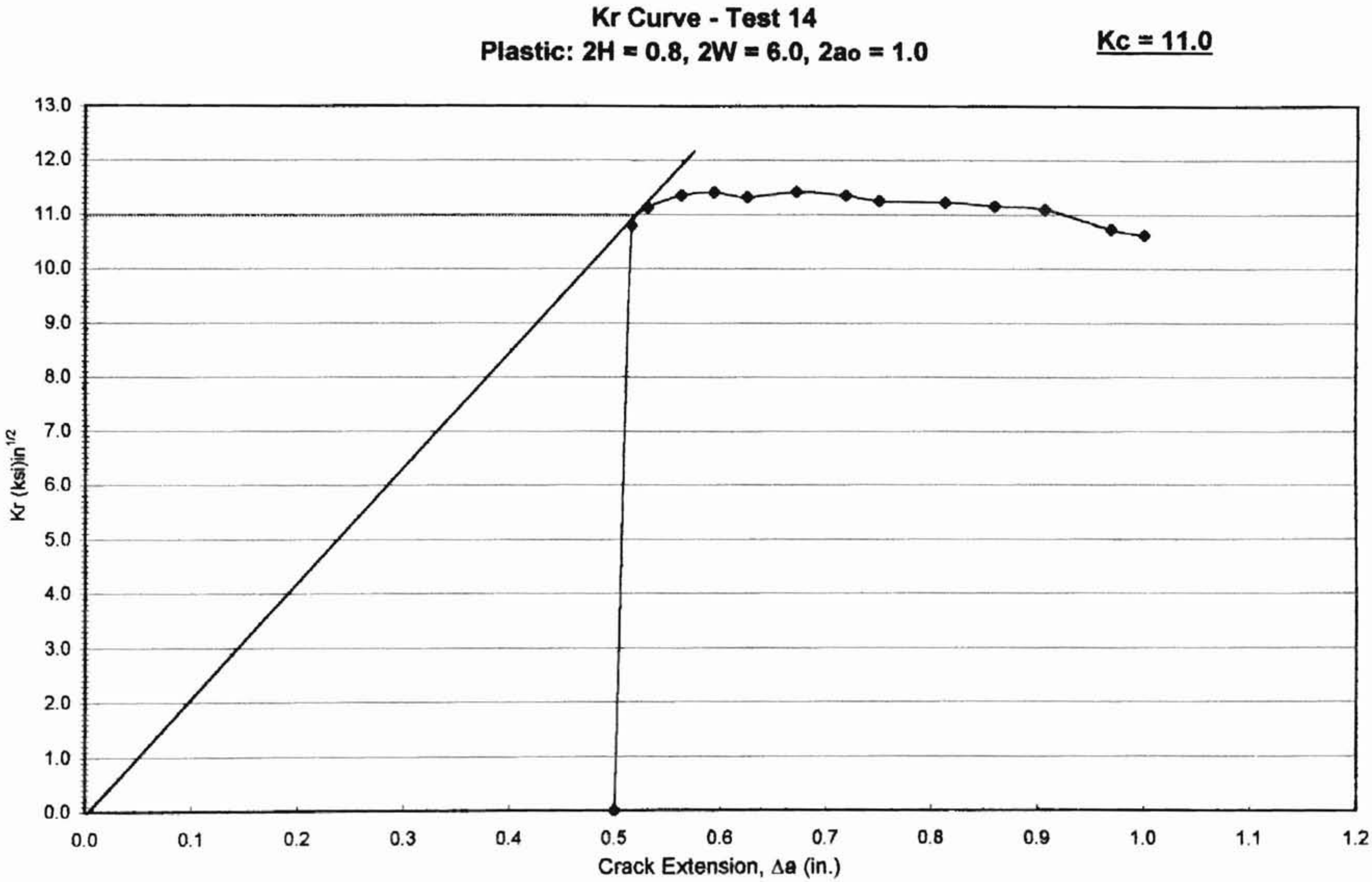

Figure 4.2.4: K_R Curve for Test 14 data (Cotterell)

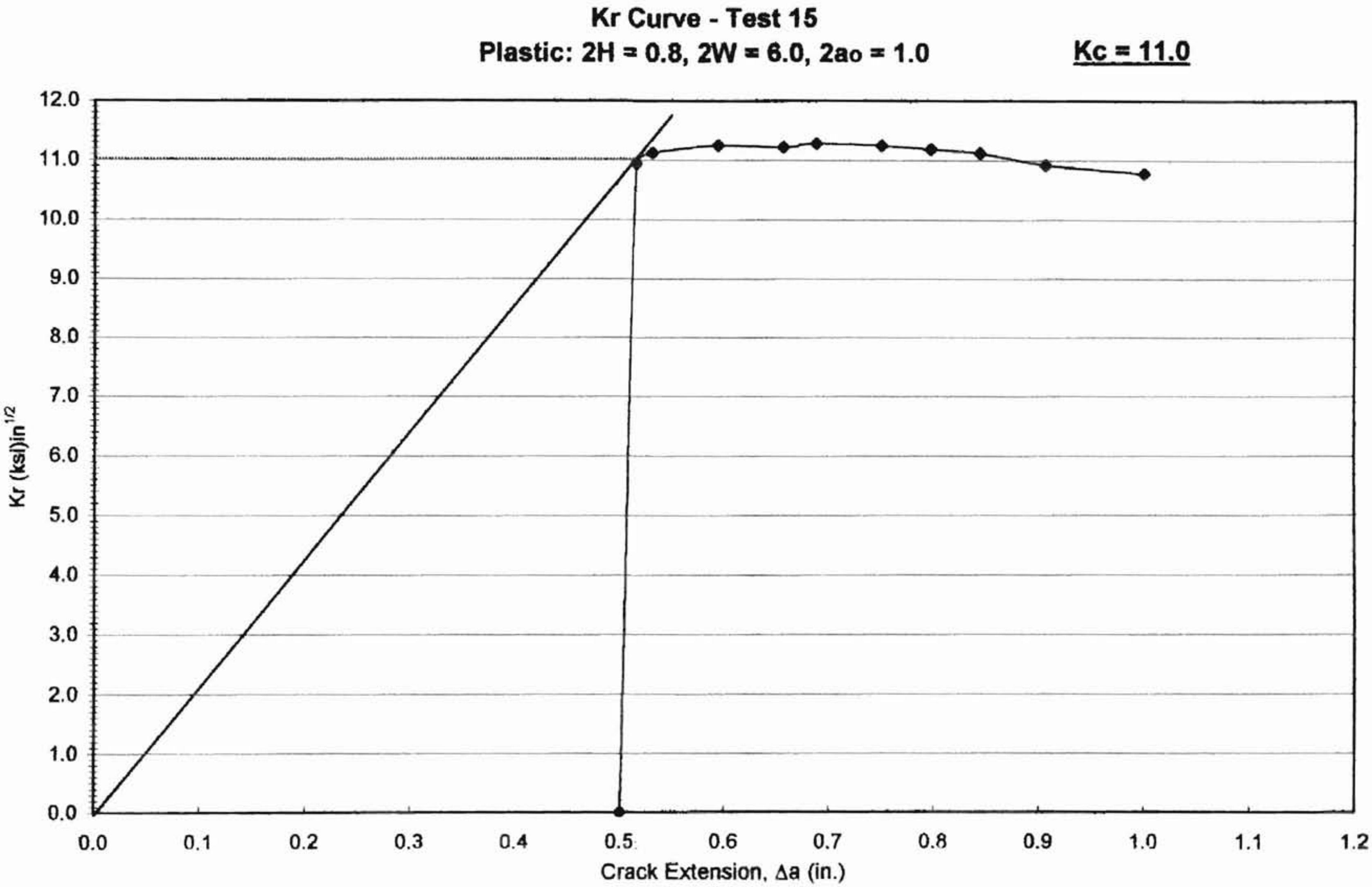

Figure 4.2.5: K_R Curve for Test 15 data (Cotterell)

Figure 4.3: K_R curves for Group 3 test runs

Group 3: Test Runs 16,17, 18, 21, 22

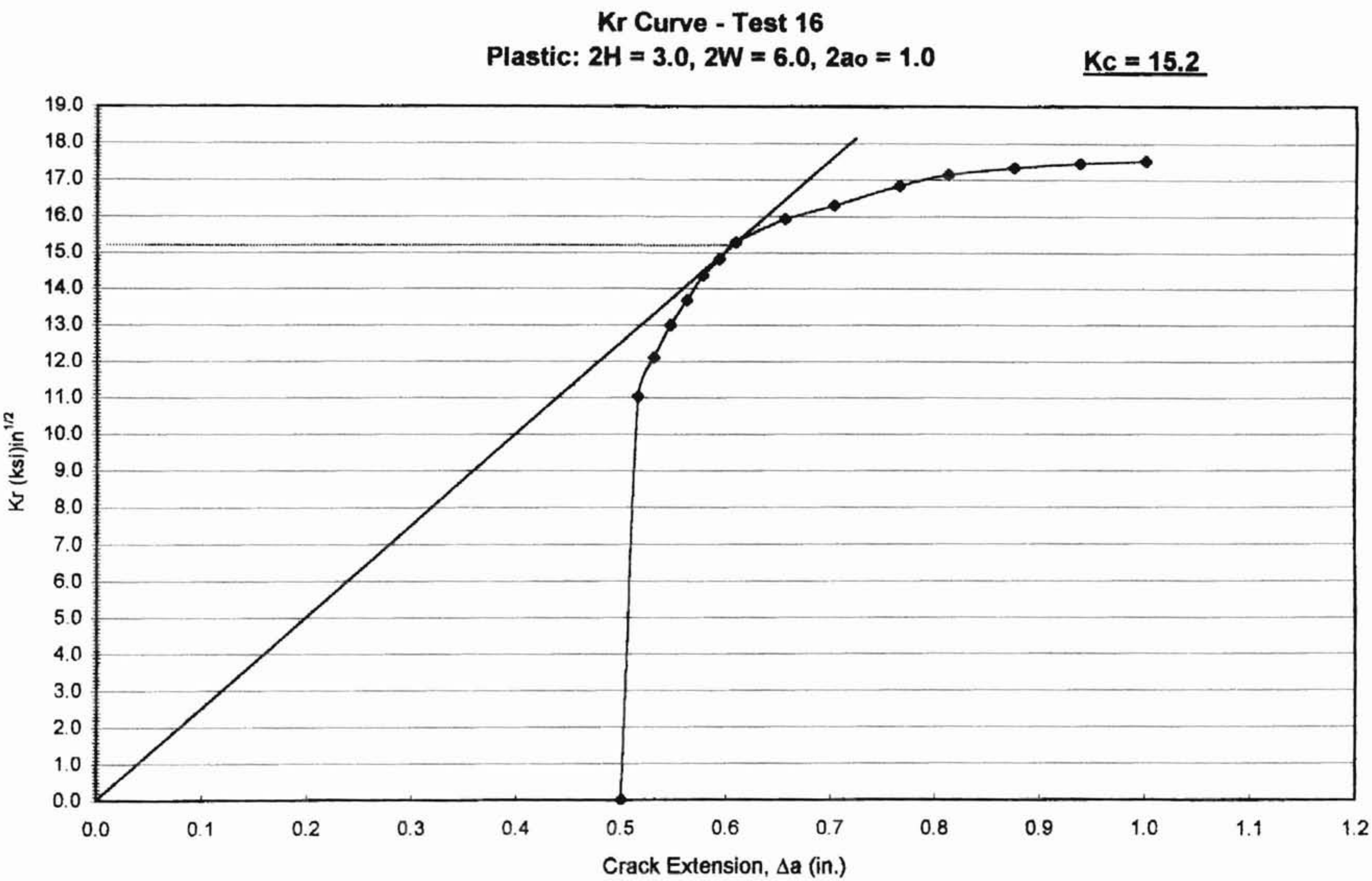

Figure 4.3.1: K_R curve for Test 16 data

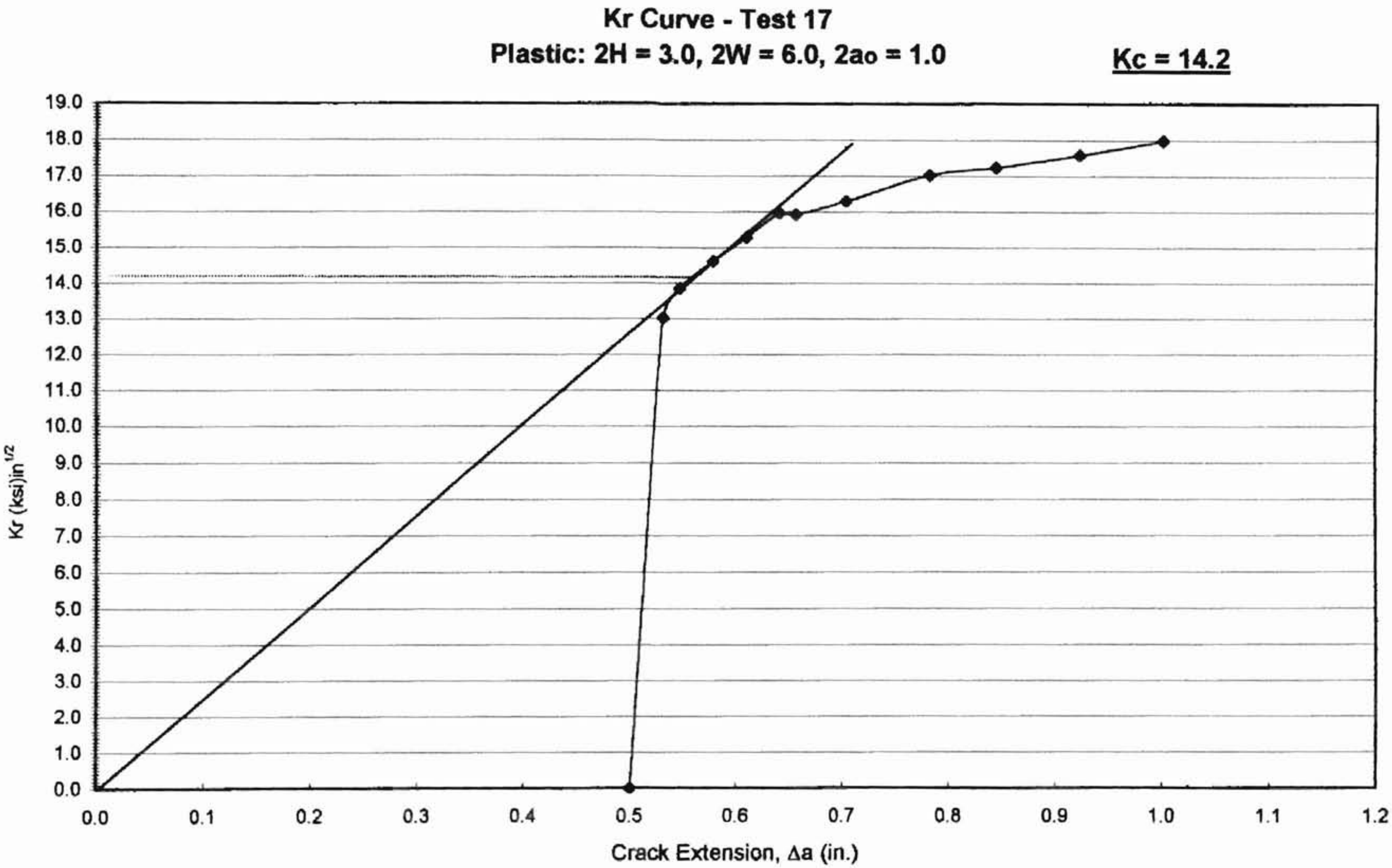

Figure 4.3.2: K_R curve for Test 17 data

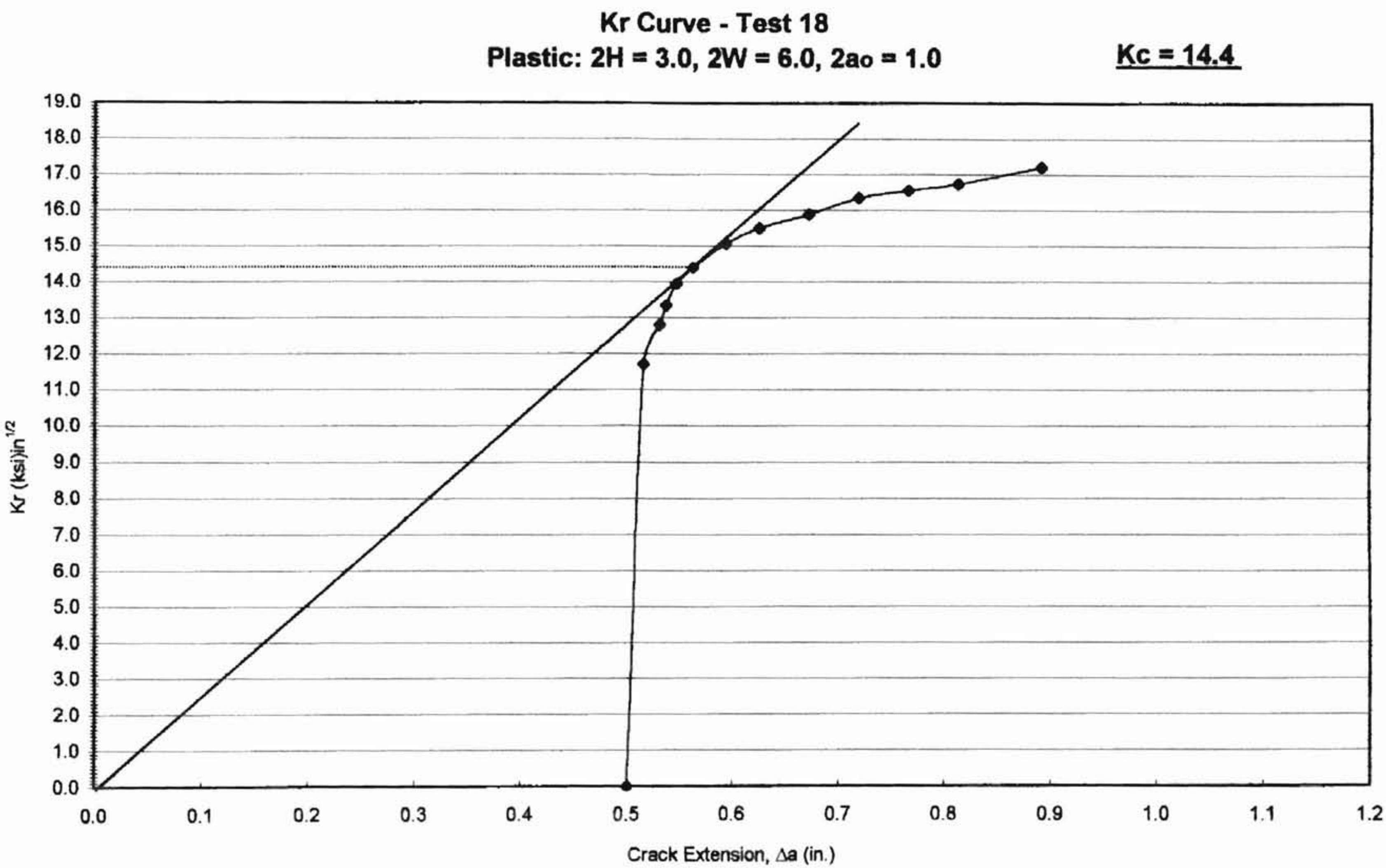

Figure 4.3.3: K_R curve for Test 18 data

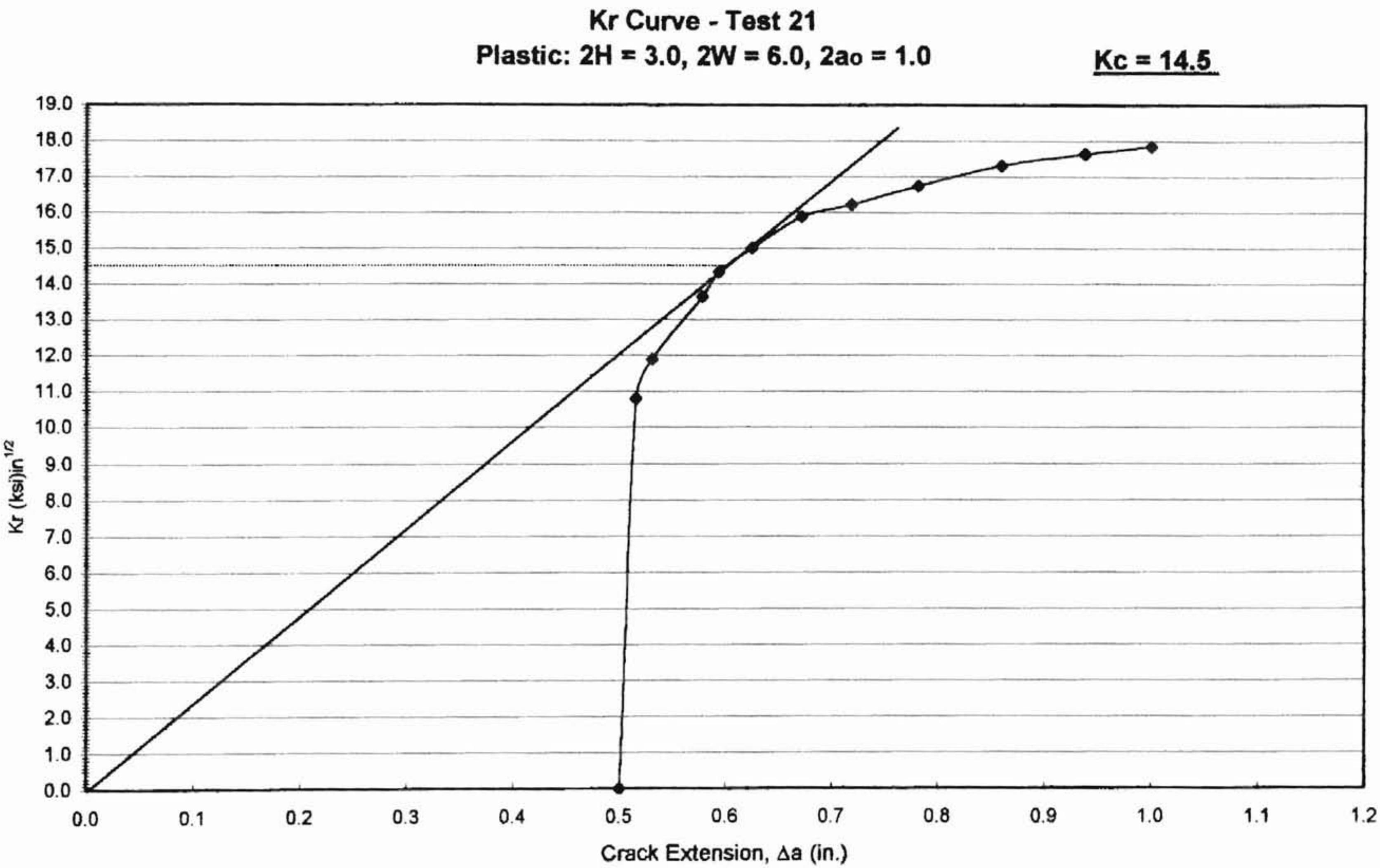

Figure 4.3.4: K_R curve for Test 21 data

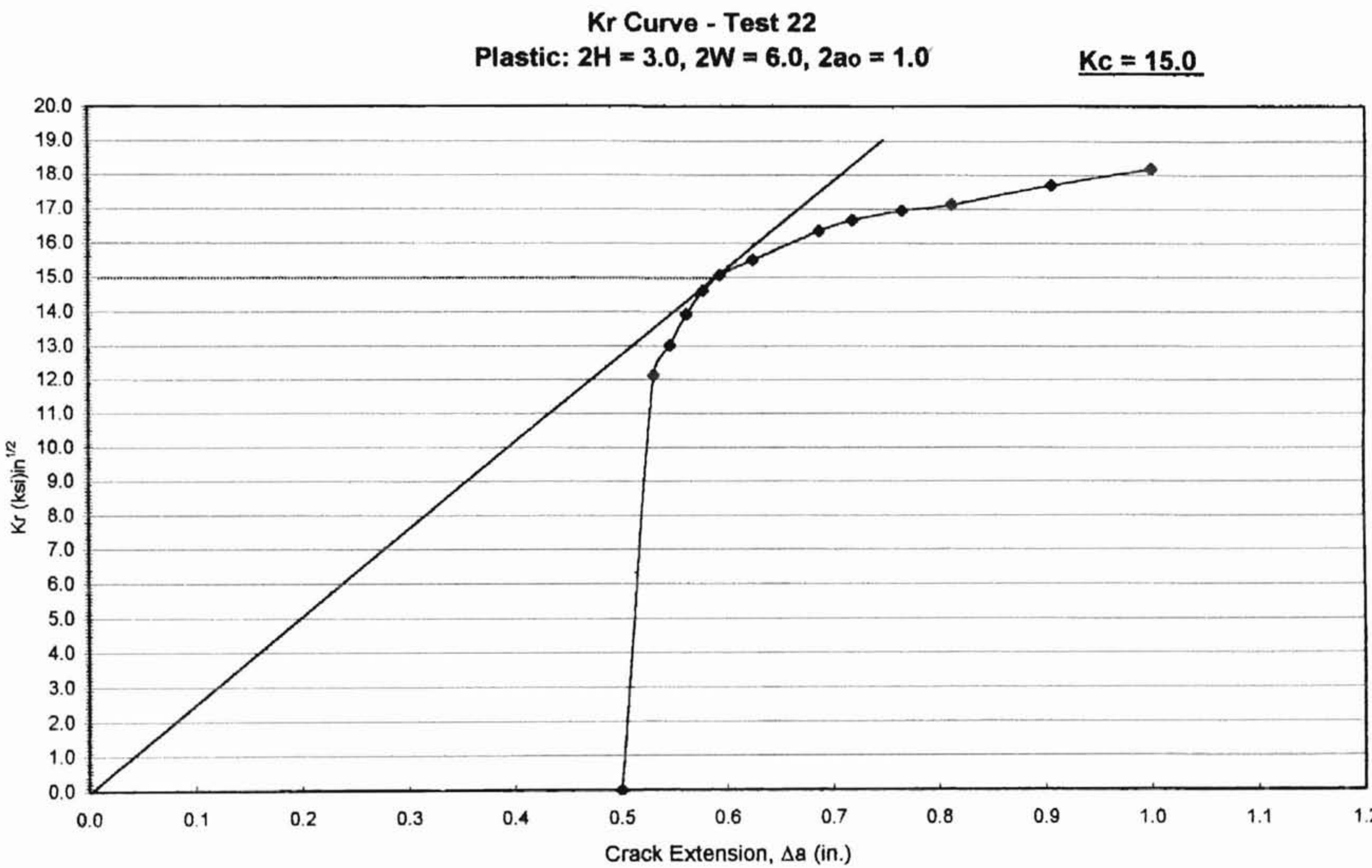

Figure 4.3.5: K_R curve for Test 22 data

Figure 4.4: K_R curves for Group 4 test runs

Group 4: Test Runs 23, 28, 31, 33, 34

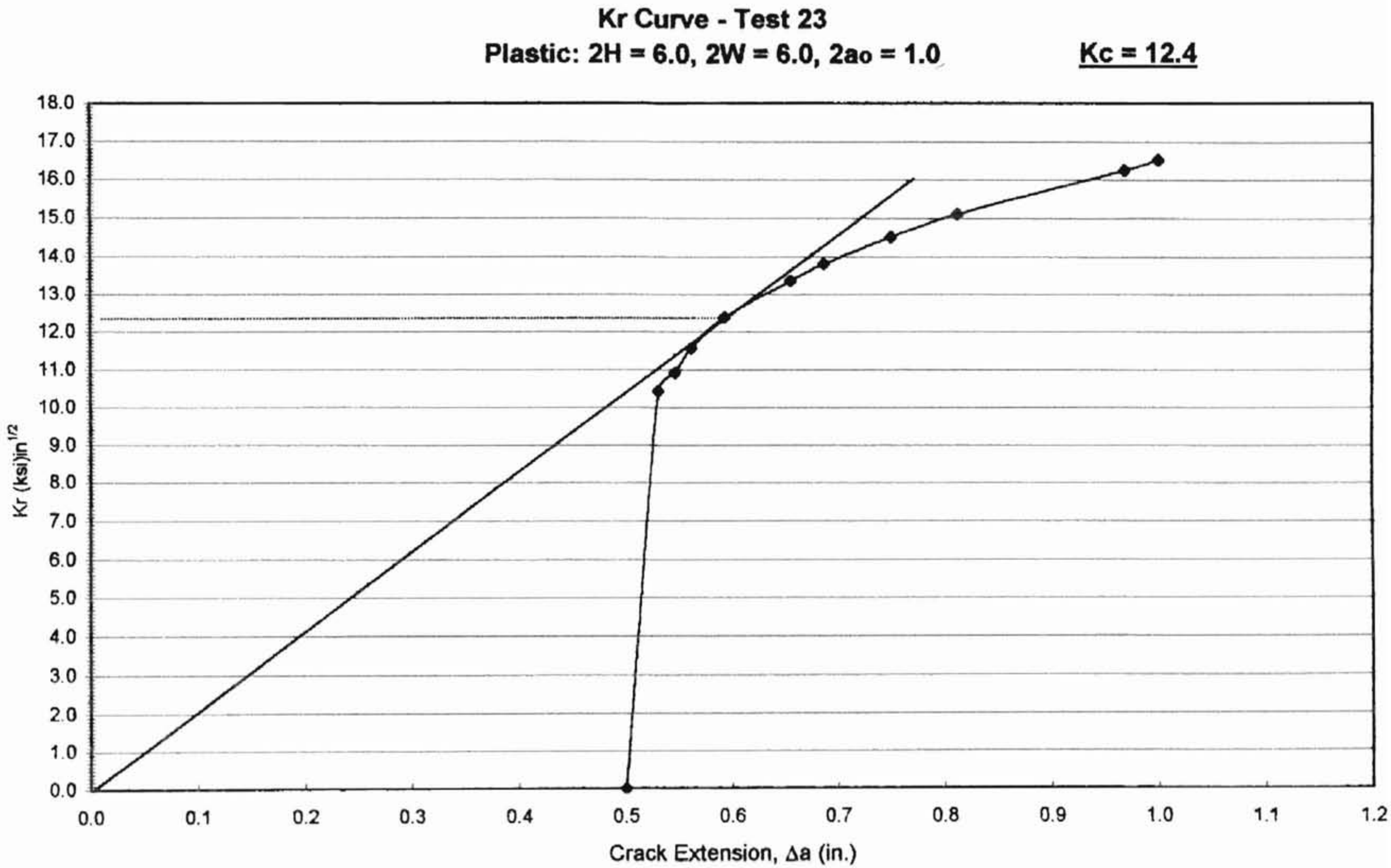

Figure 4.4.1: K_R curve for Test 23 data

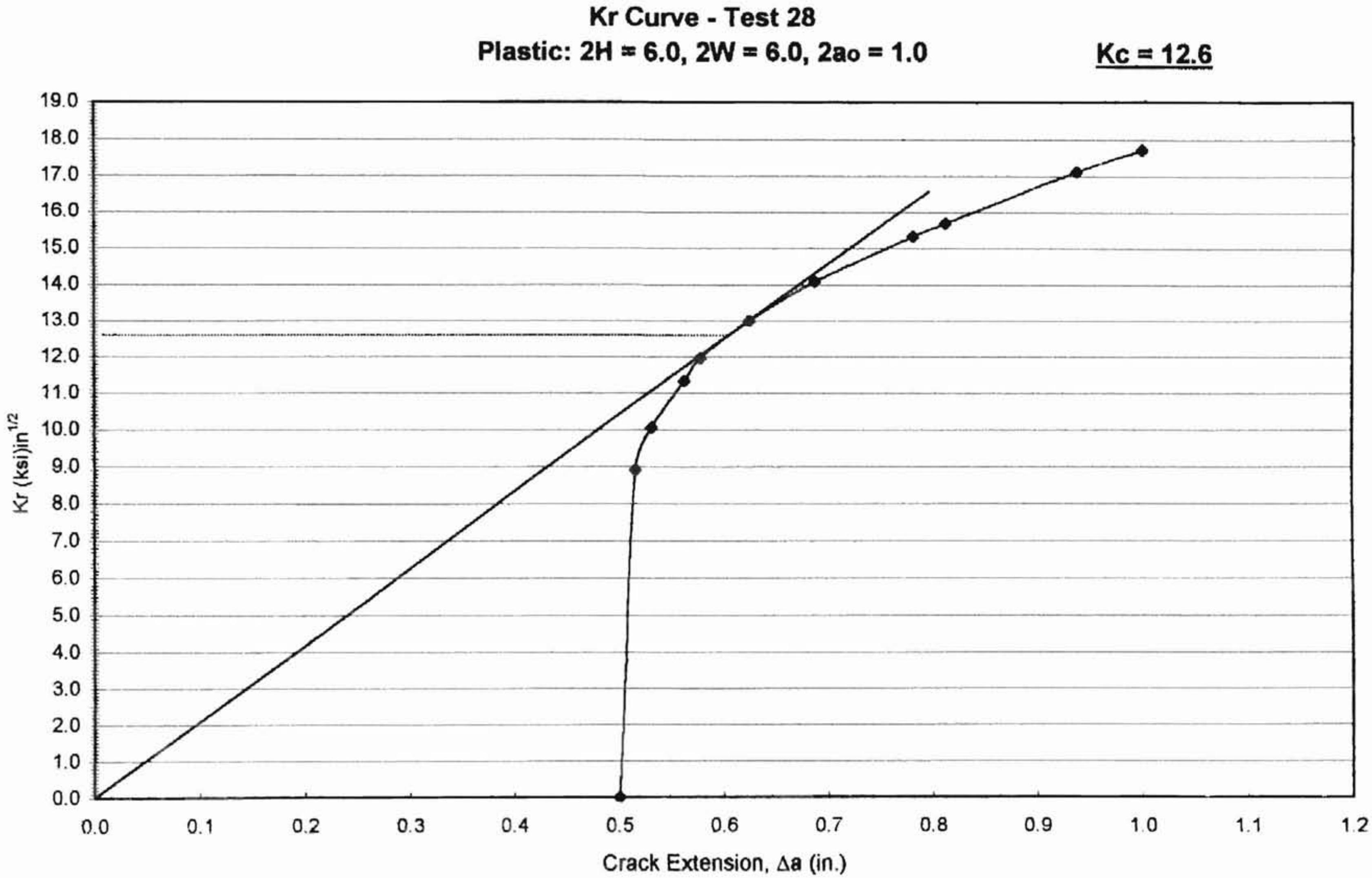

Figure 4.4.2: K_R curve for Test 28 data

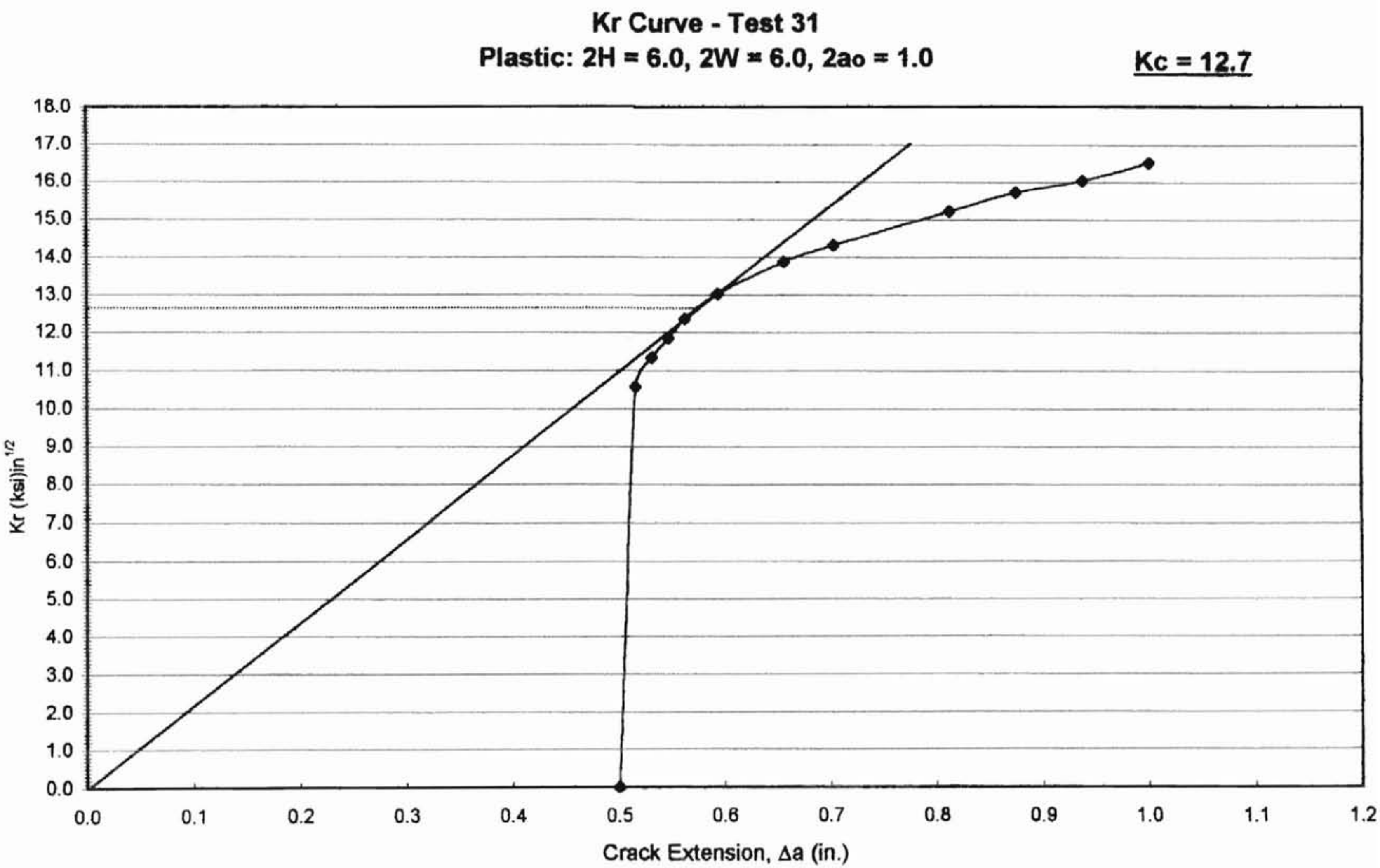

Figure 4.4.3: K_R curve for Test 31 data

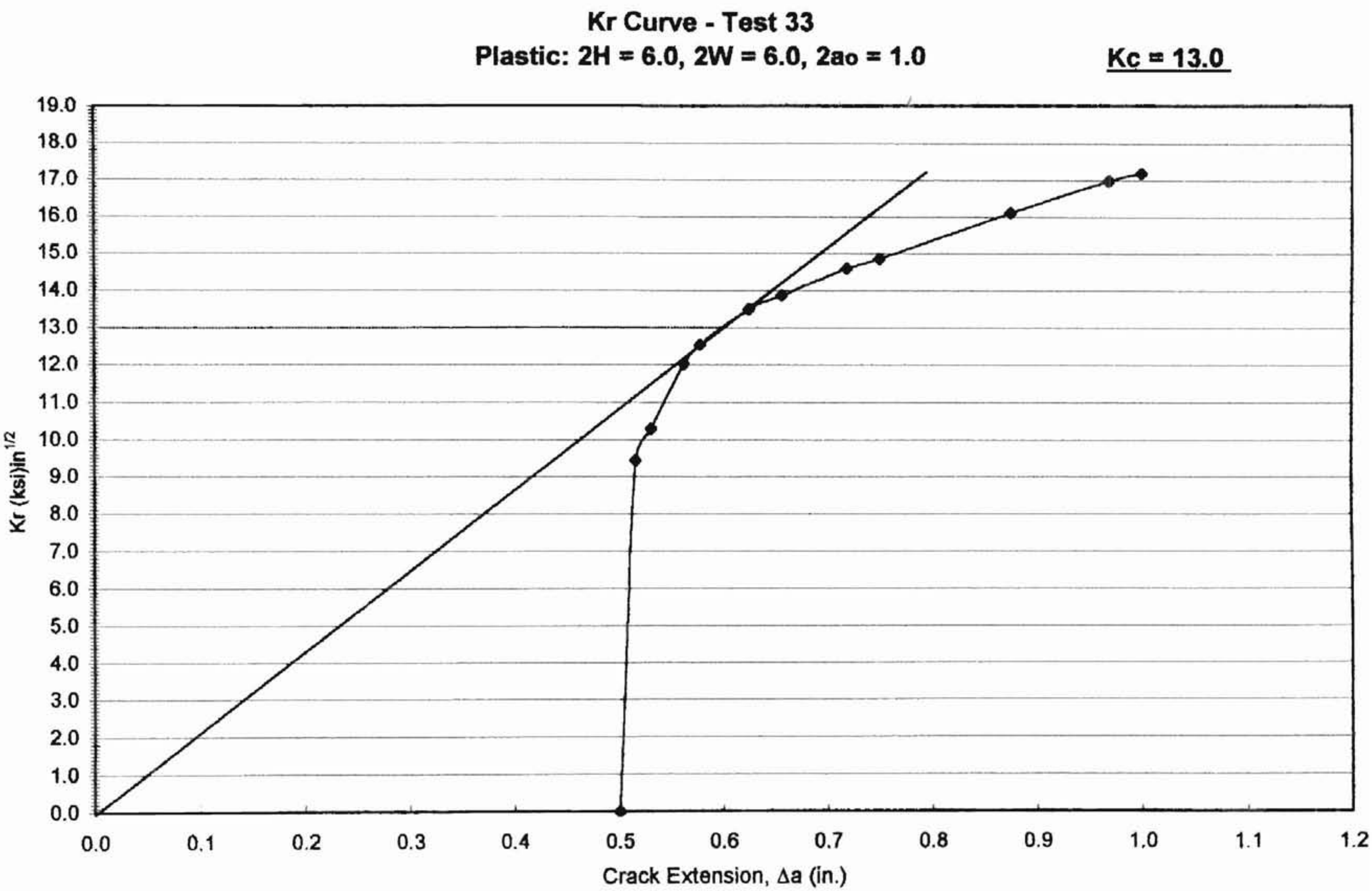

Figure 4.4.4: K_R curve for Test 33 data

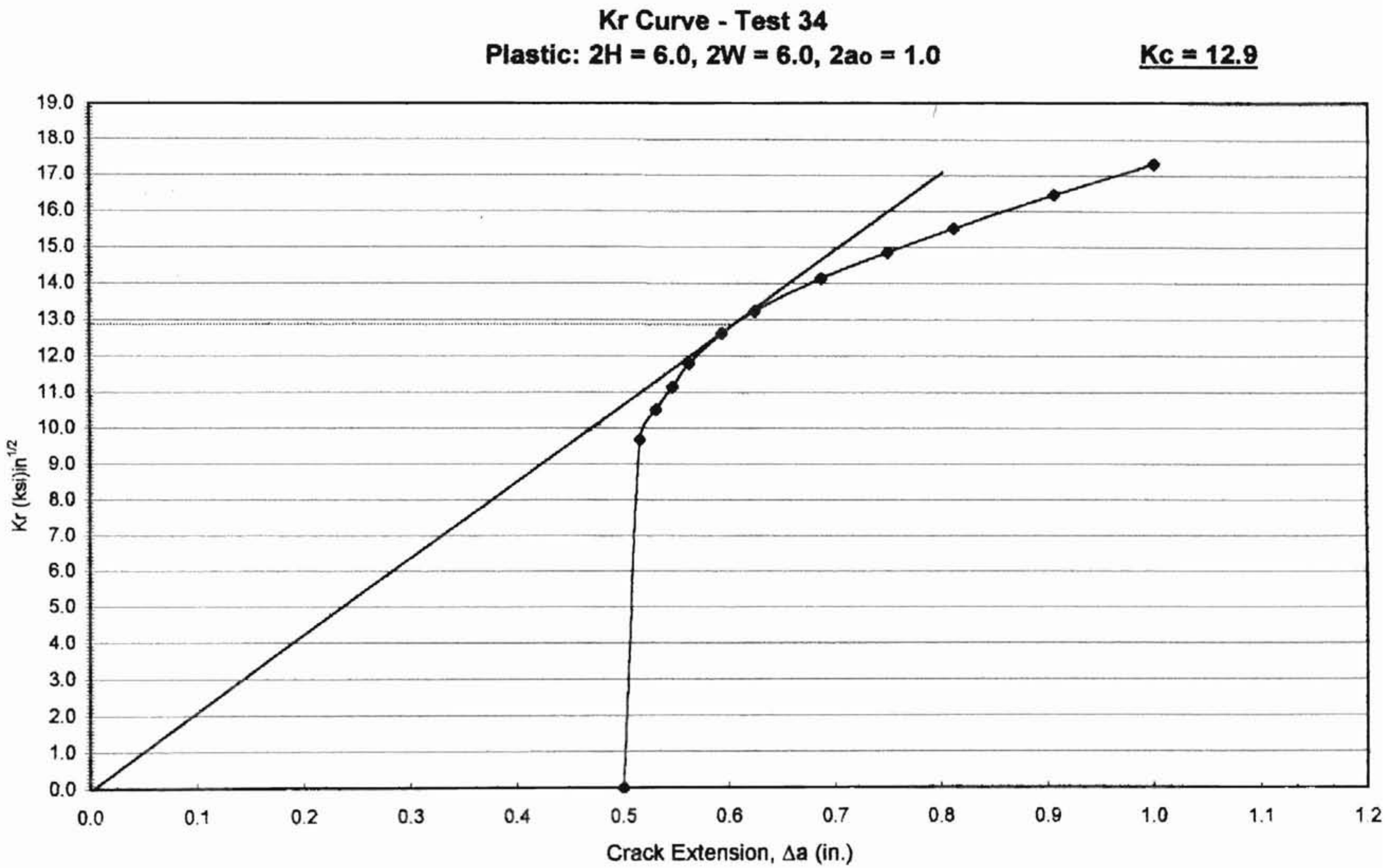

Figure 4.4.5: K_R curve for Test 34 data

Figure 4.5: K_R curves for Group 5 test runs

Group 5: Test Runs 36, 37, 38, 40, 41

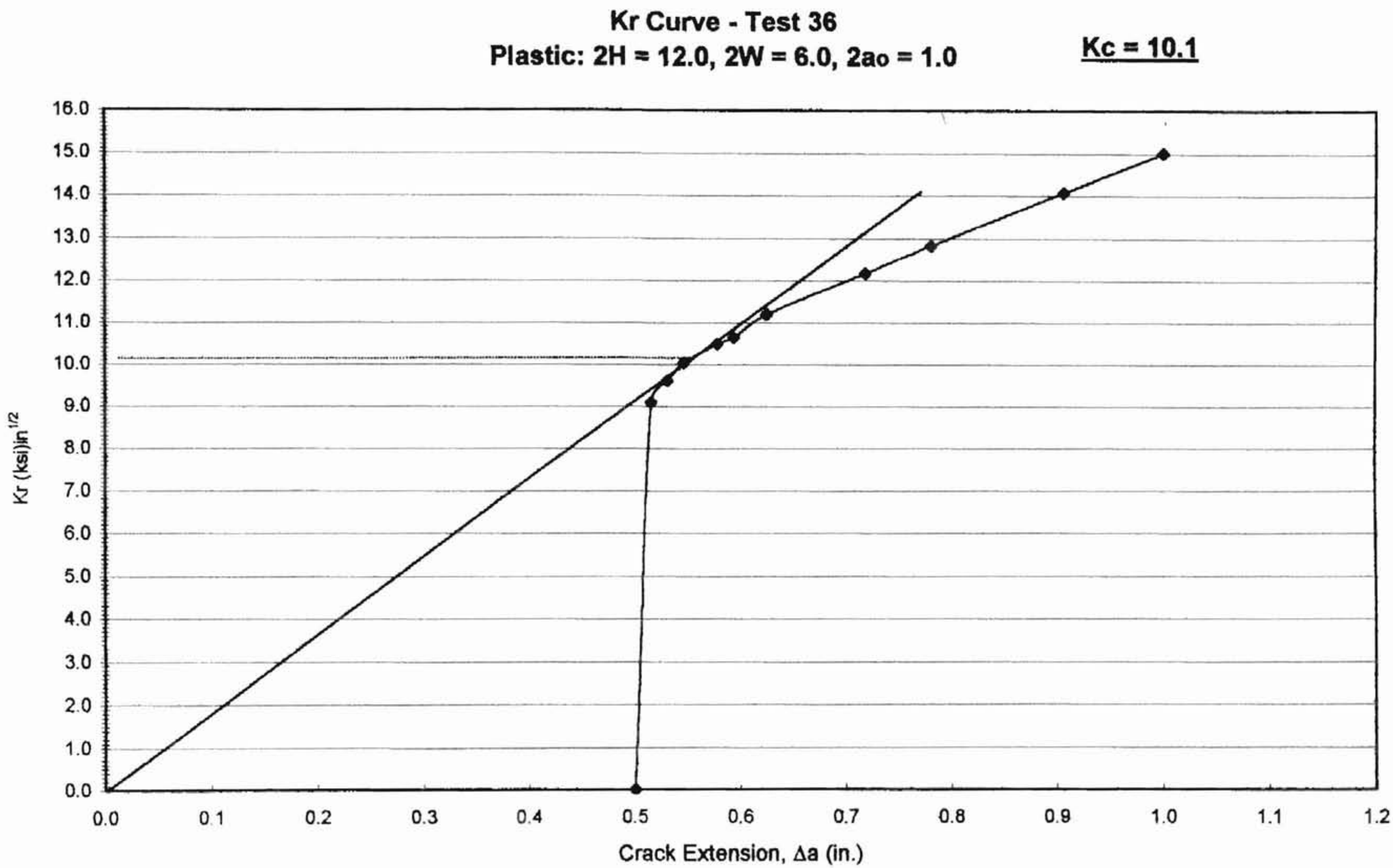

Figure 4.5.1: K_R curve for Test 36 data

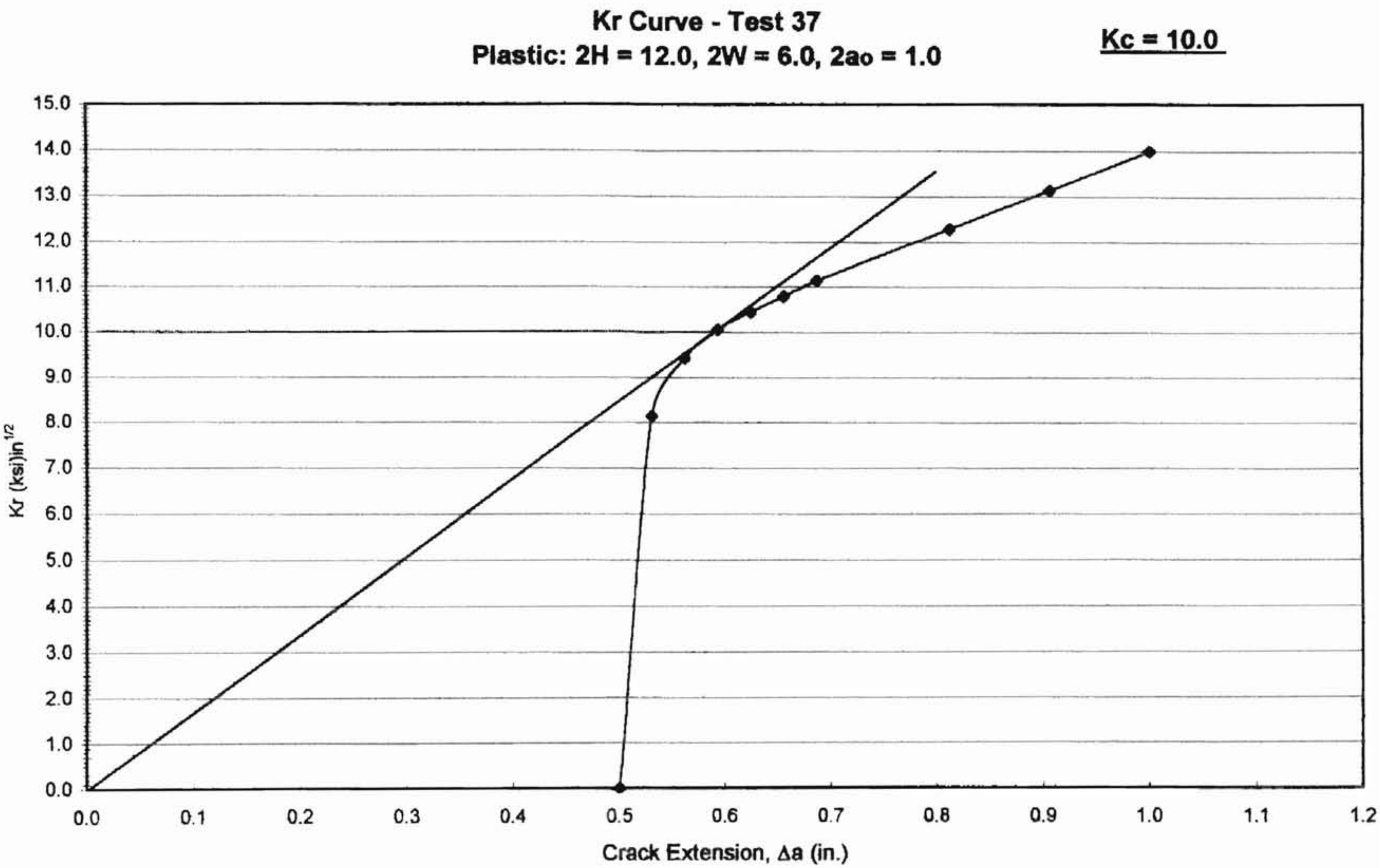

Figure 4.5.2: K_R curve for Test 37 data

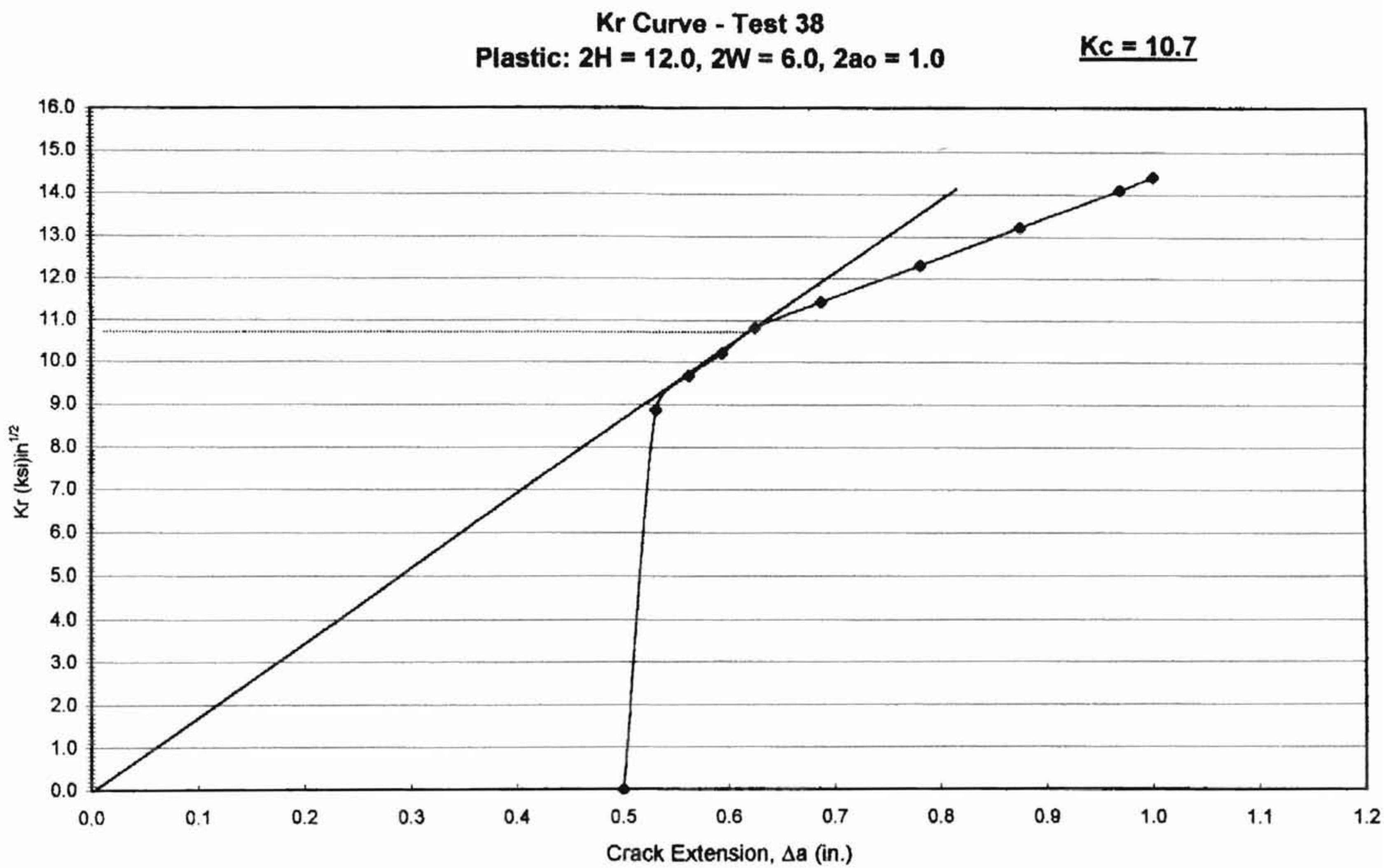

Figure 4.5.3: K_R curve for Test 38 data

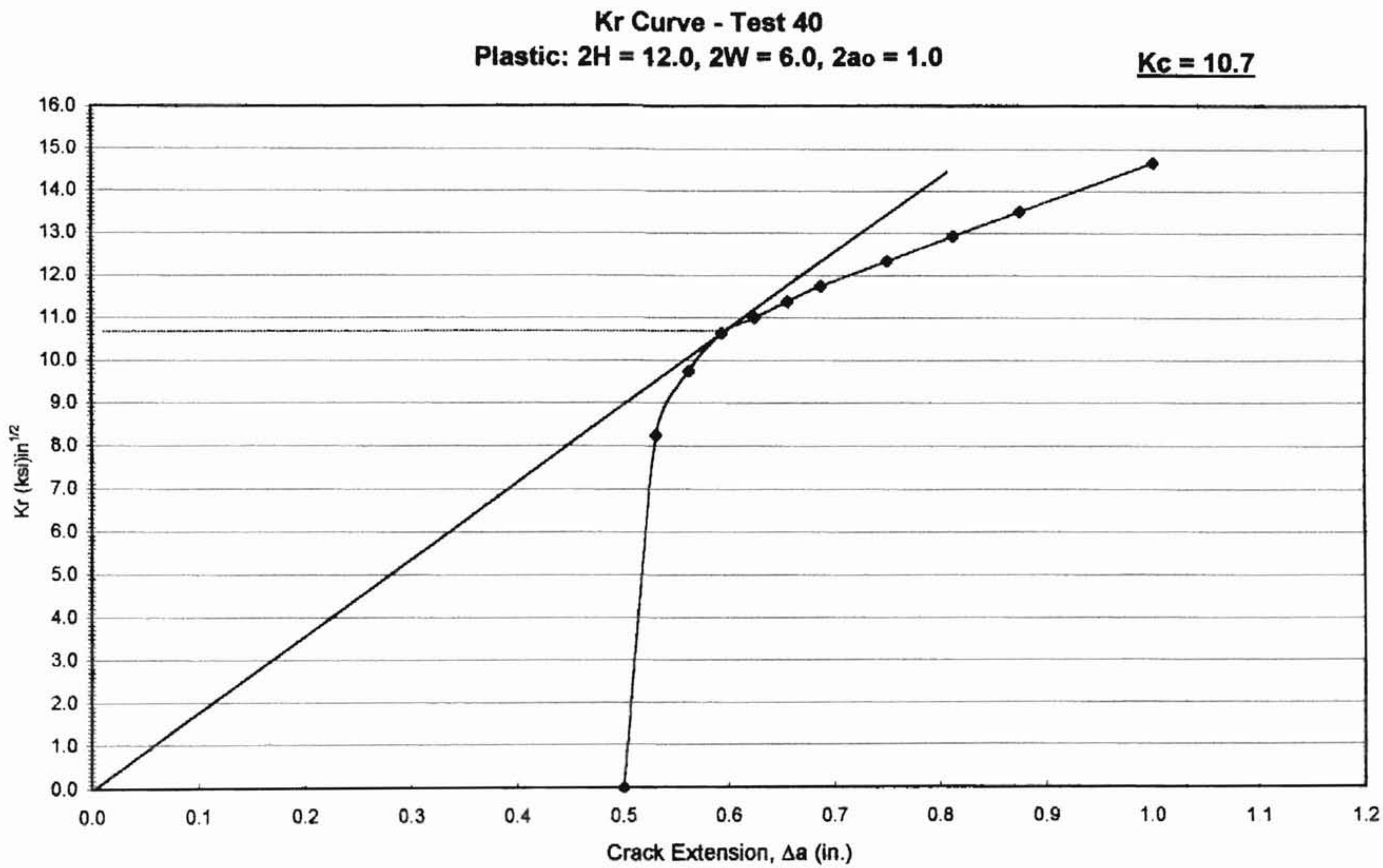

Figure 4.5.4: K_R curve for Test 40 data

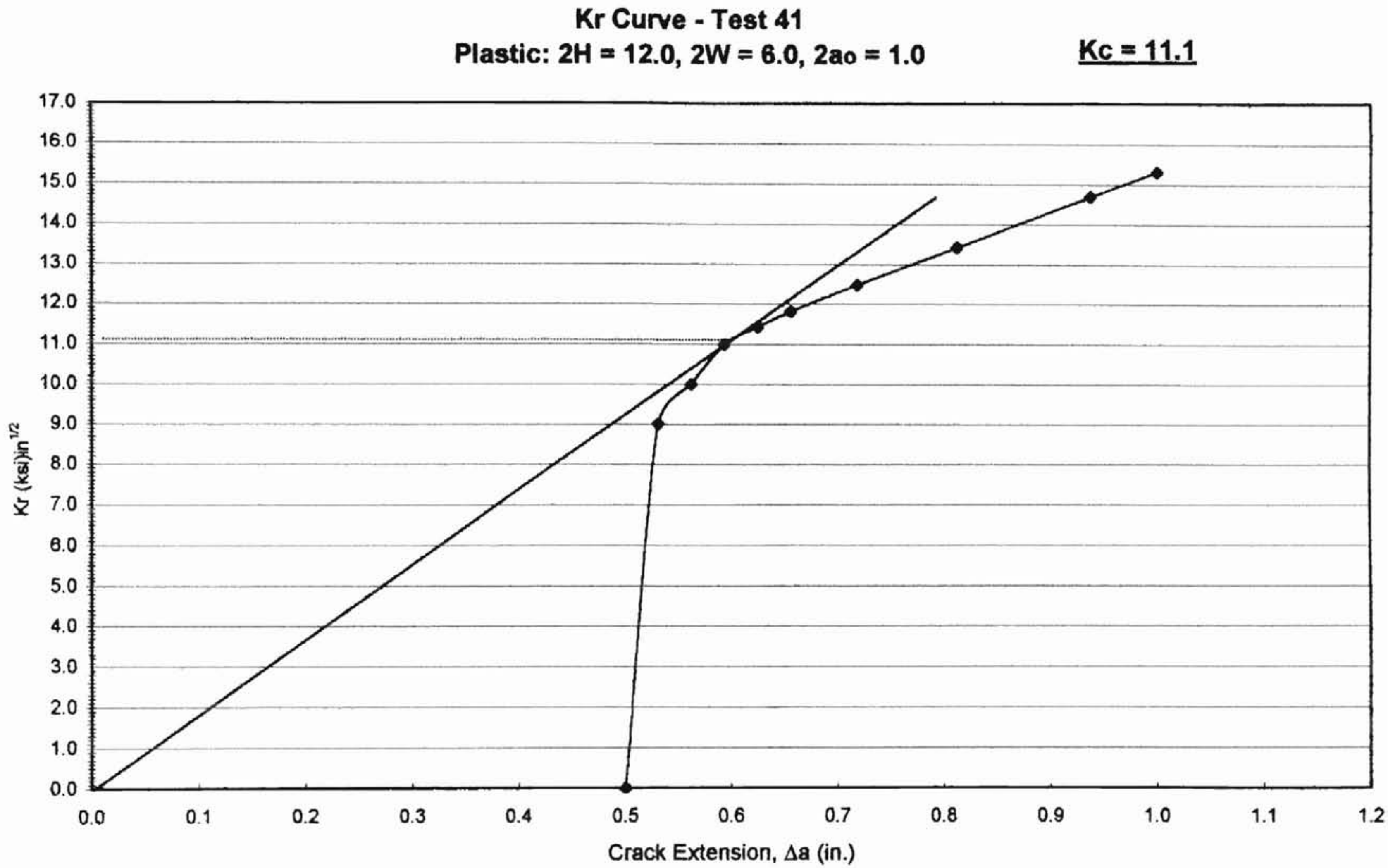

Figure 4.5.5: K_R curve for Test 41 data

Figure 4.6 K_R curves for Group 6 test runs

Group 6: Test Runs 42, 45, 46, 48, 49

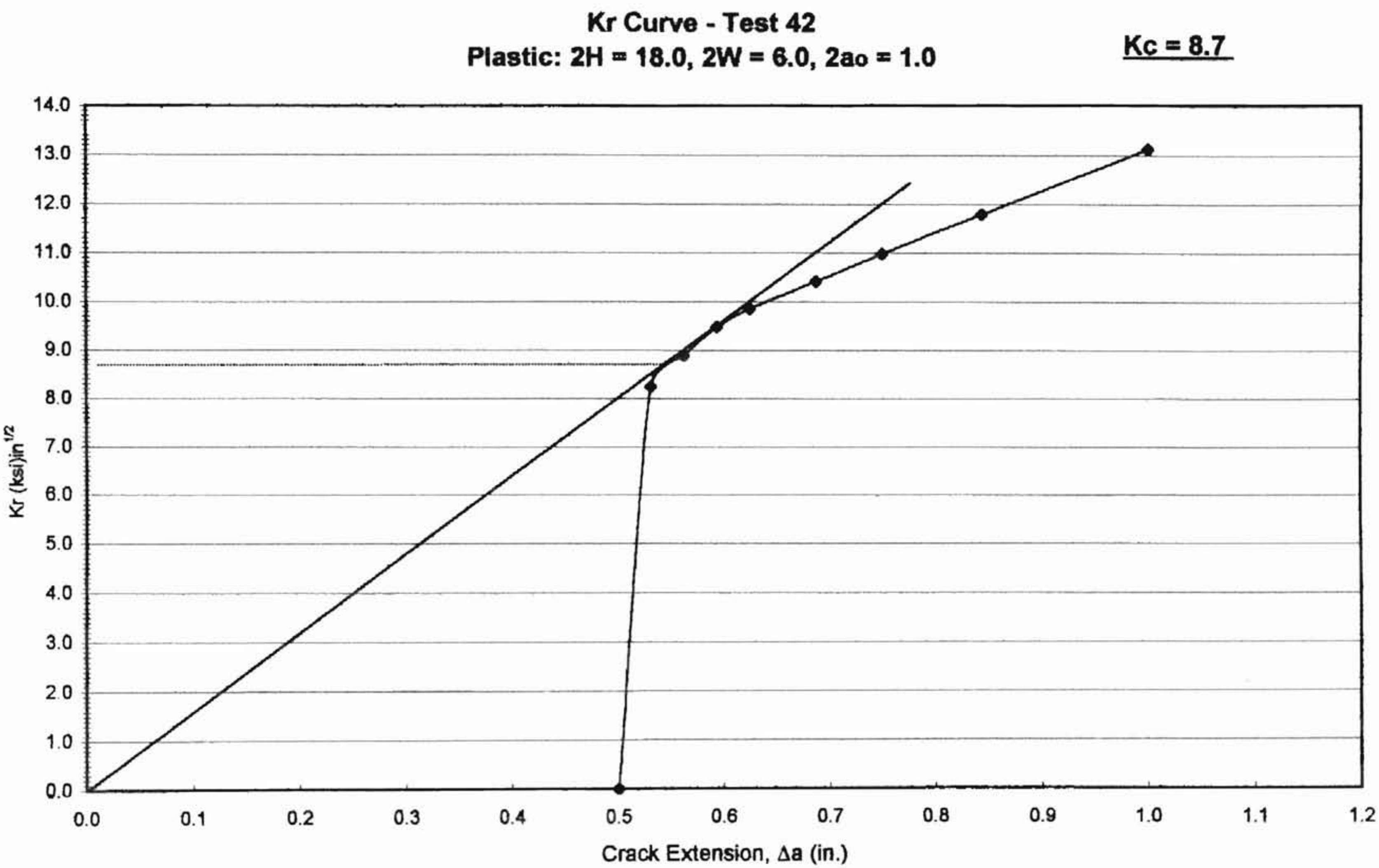

Figure 4.6.1: K_R curve for Test 42 data

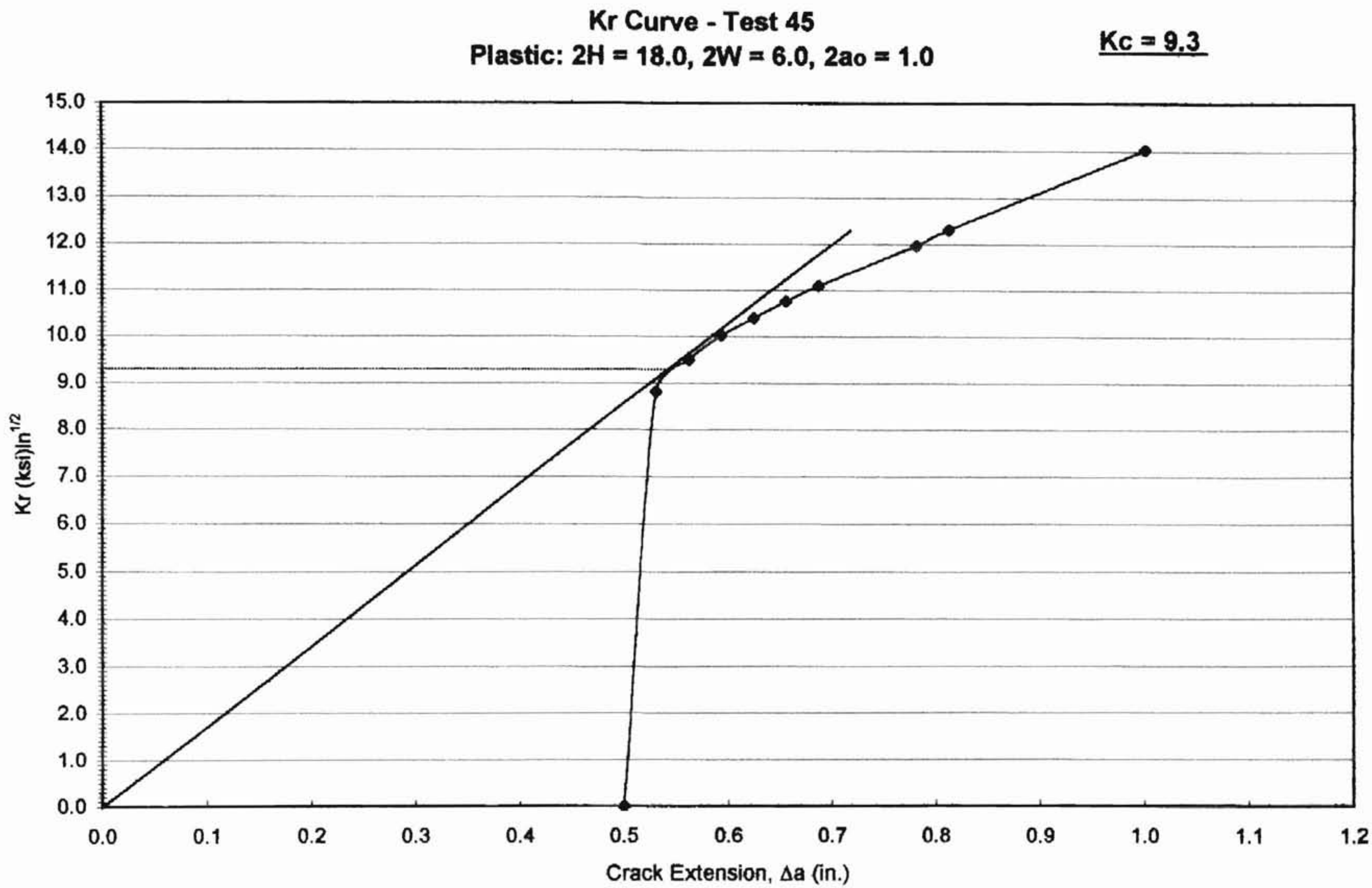

Figure 4.6.2: K_R curve for Test 45 data

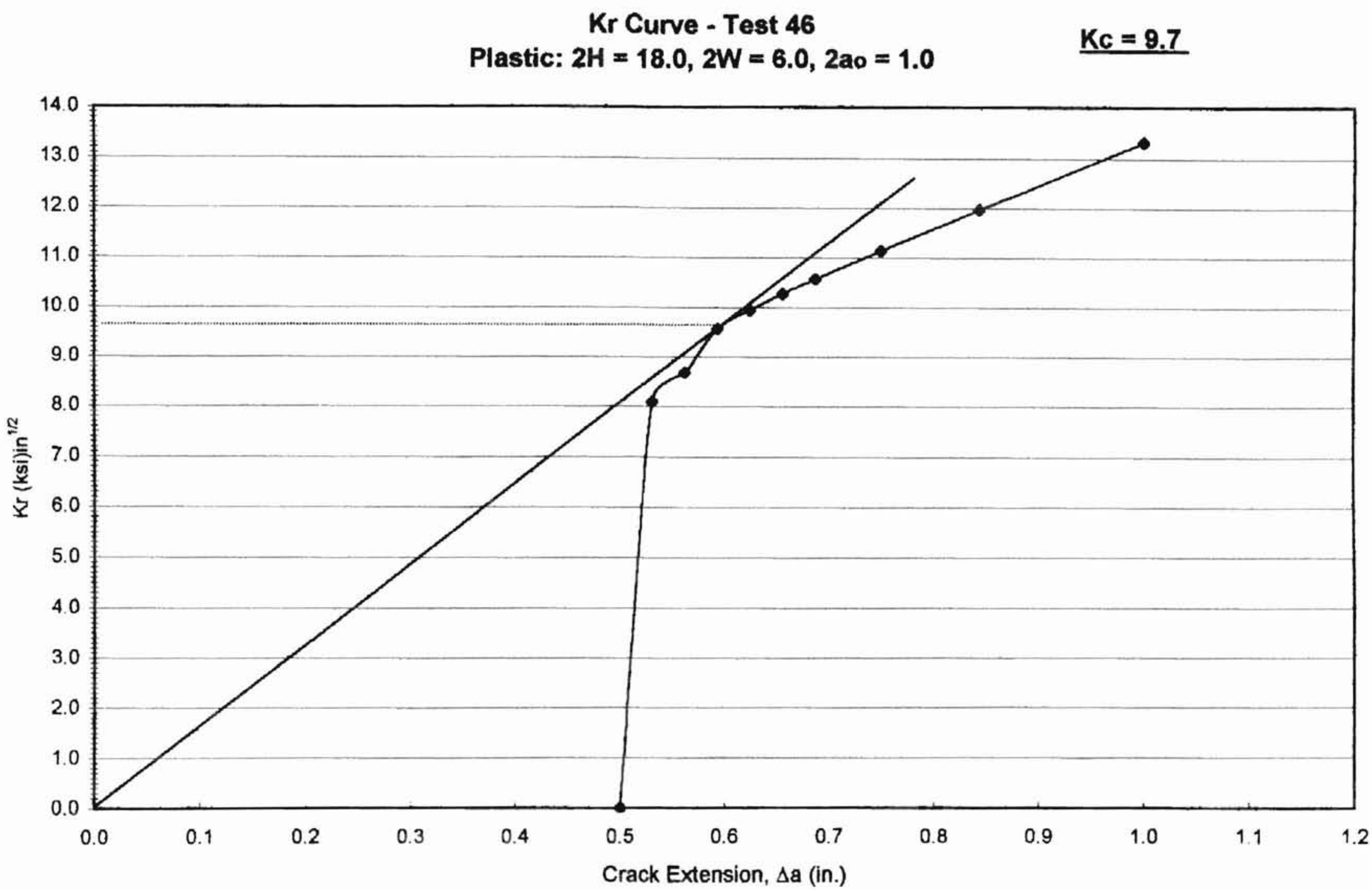

Figure 4.6.3: K_R curve for Test 46 data

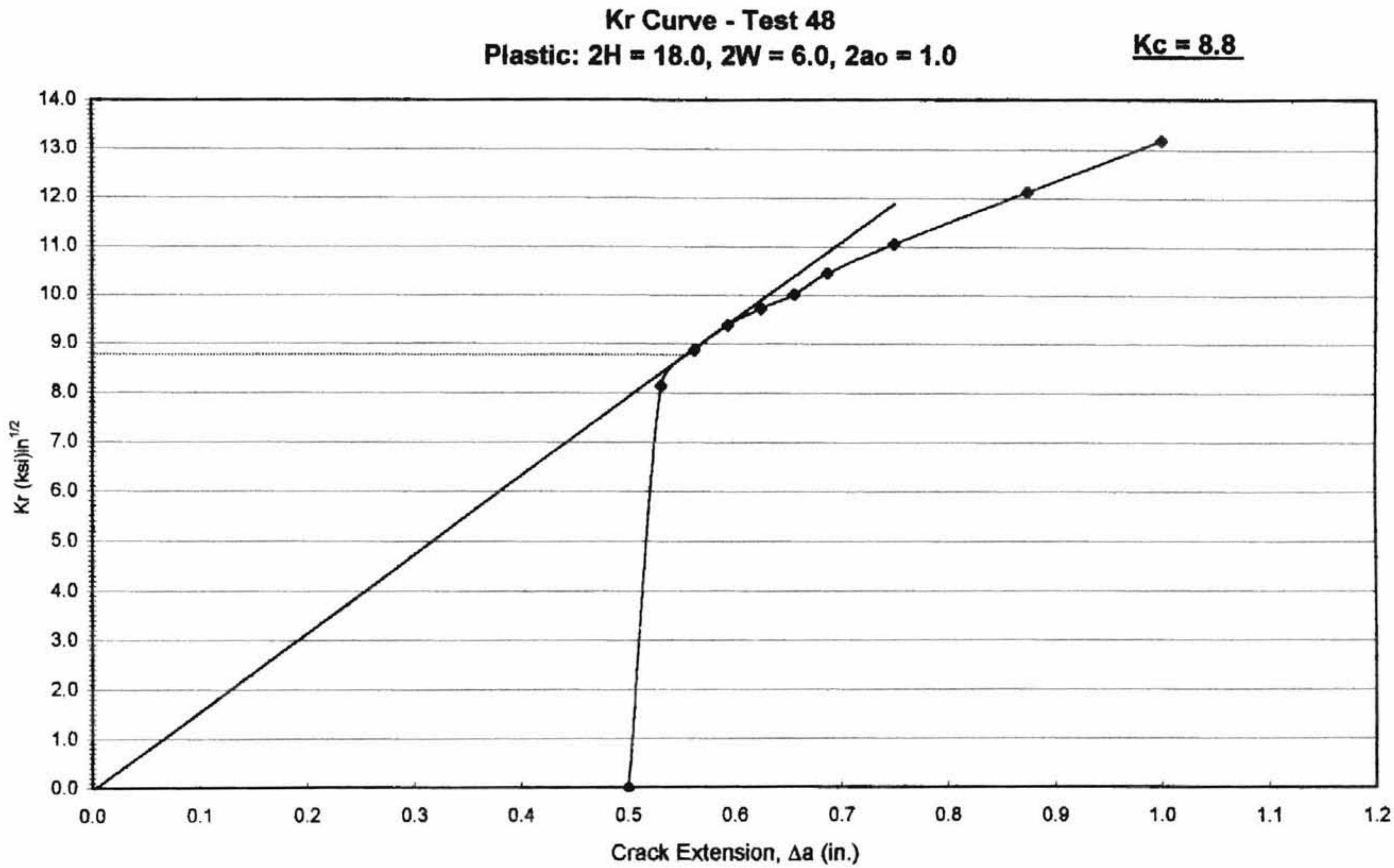

Figure 4.6.4: K_R curve for Test 48 data

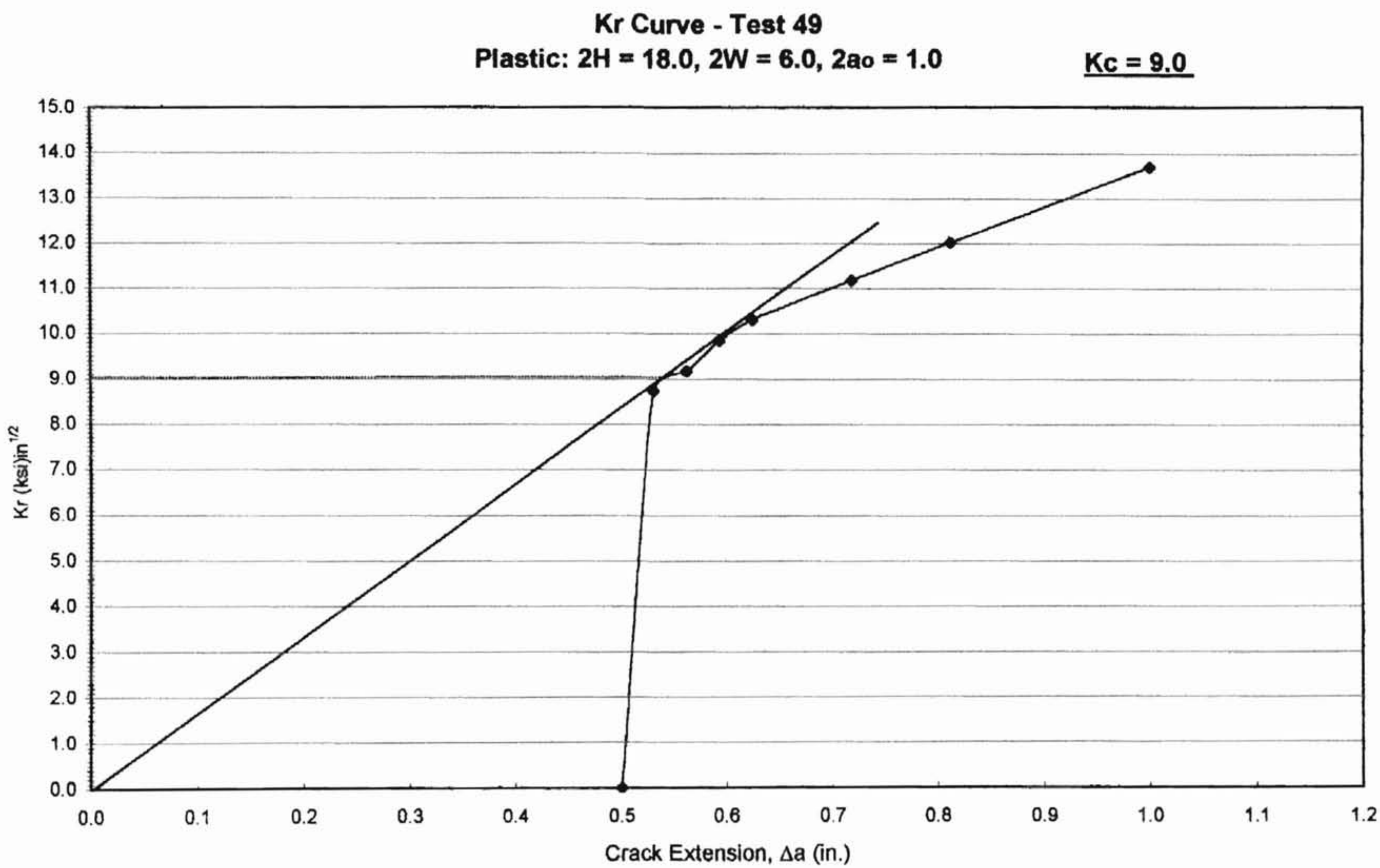

Figure 4.6.5: K_R curve for Test 49 data

Figure 4.7: K_R curves for Group 7 test runs

Group 7: Test Runs 51, 54, 56, 57, 60

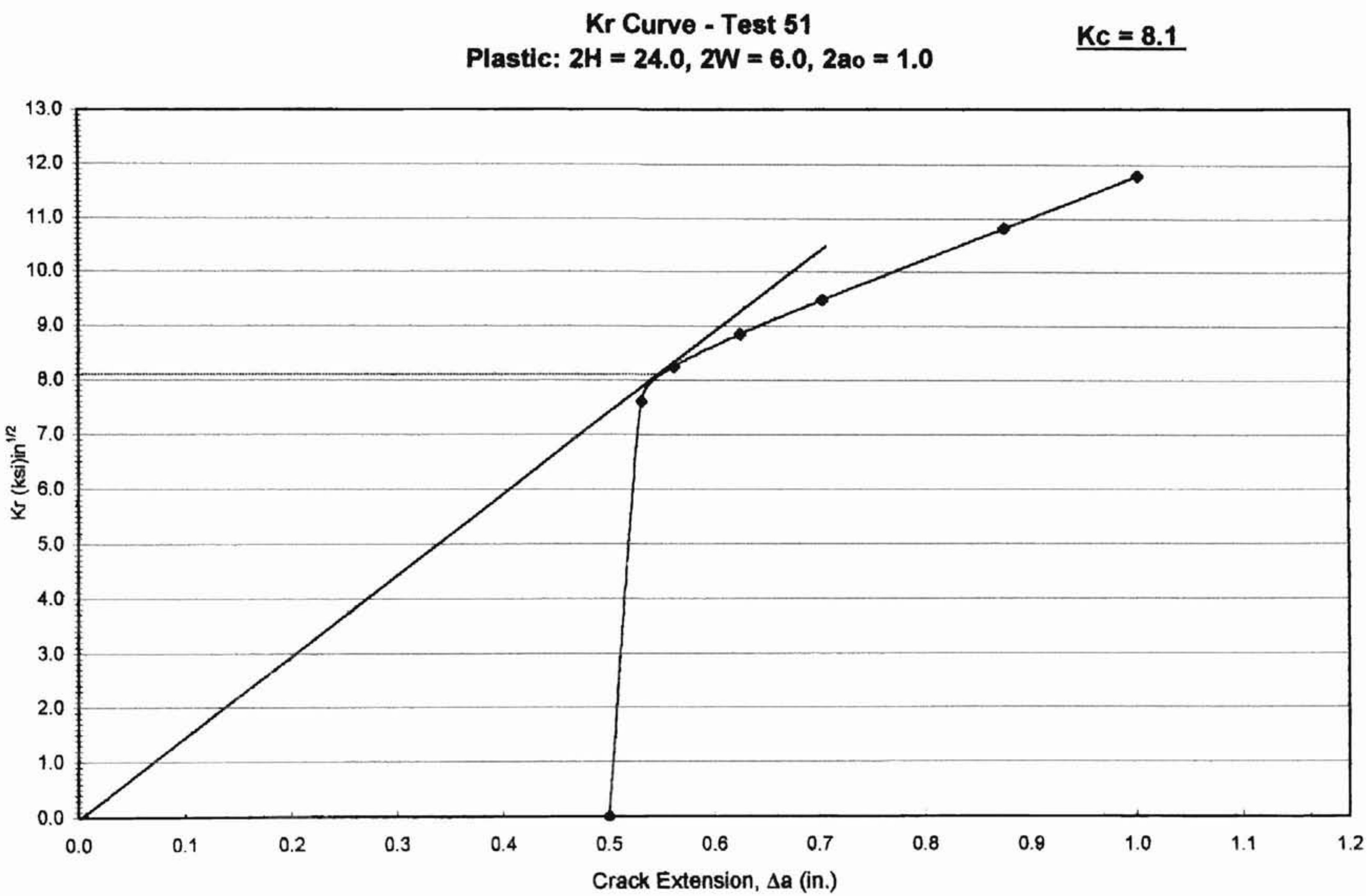

Figure 4.7.1: K_R curve for Test 51 data

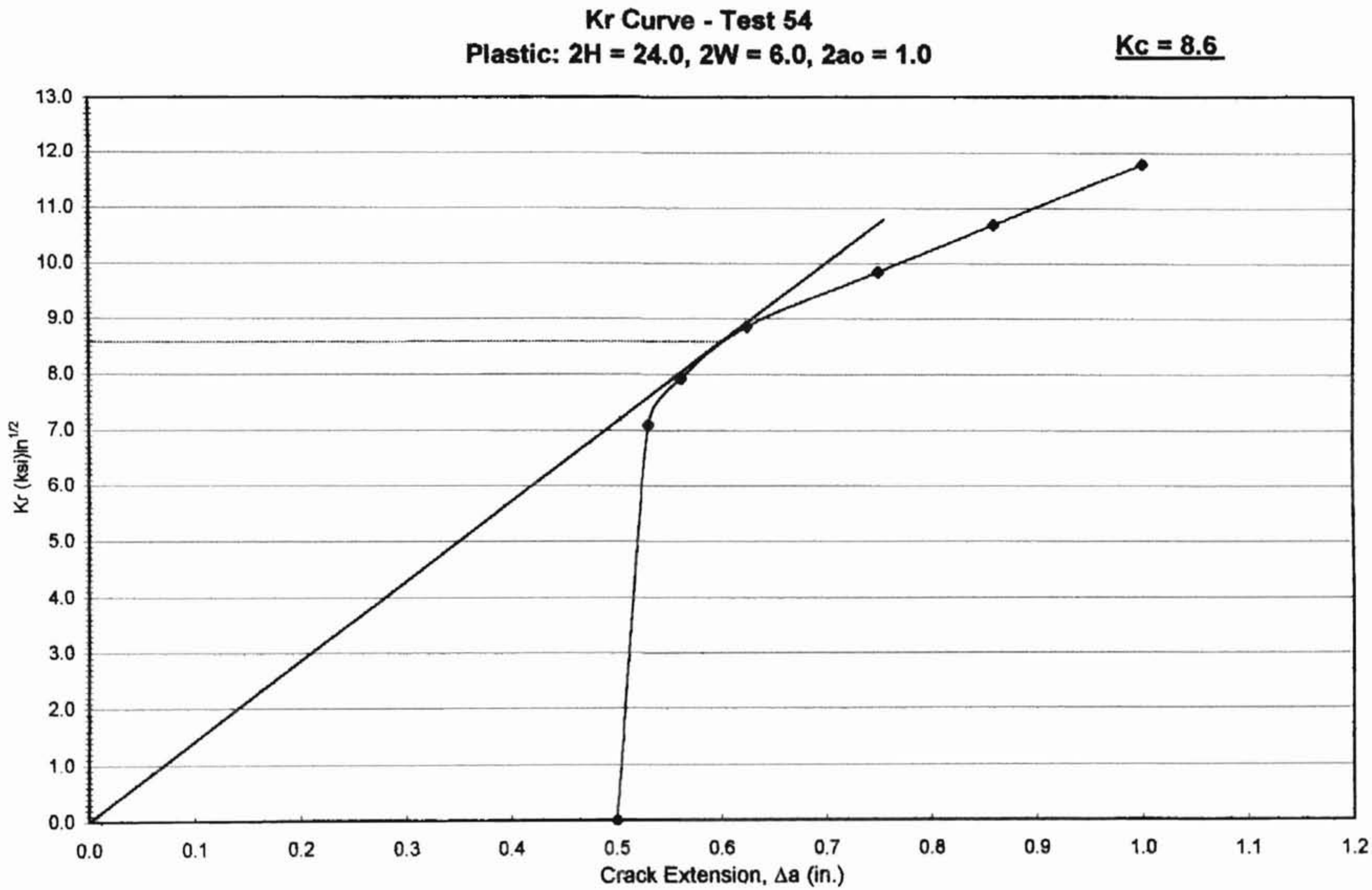

Figure 4.7.2: K_R curve for Test 54 data

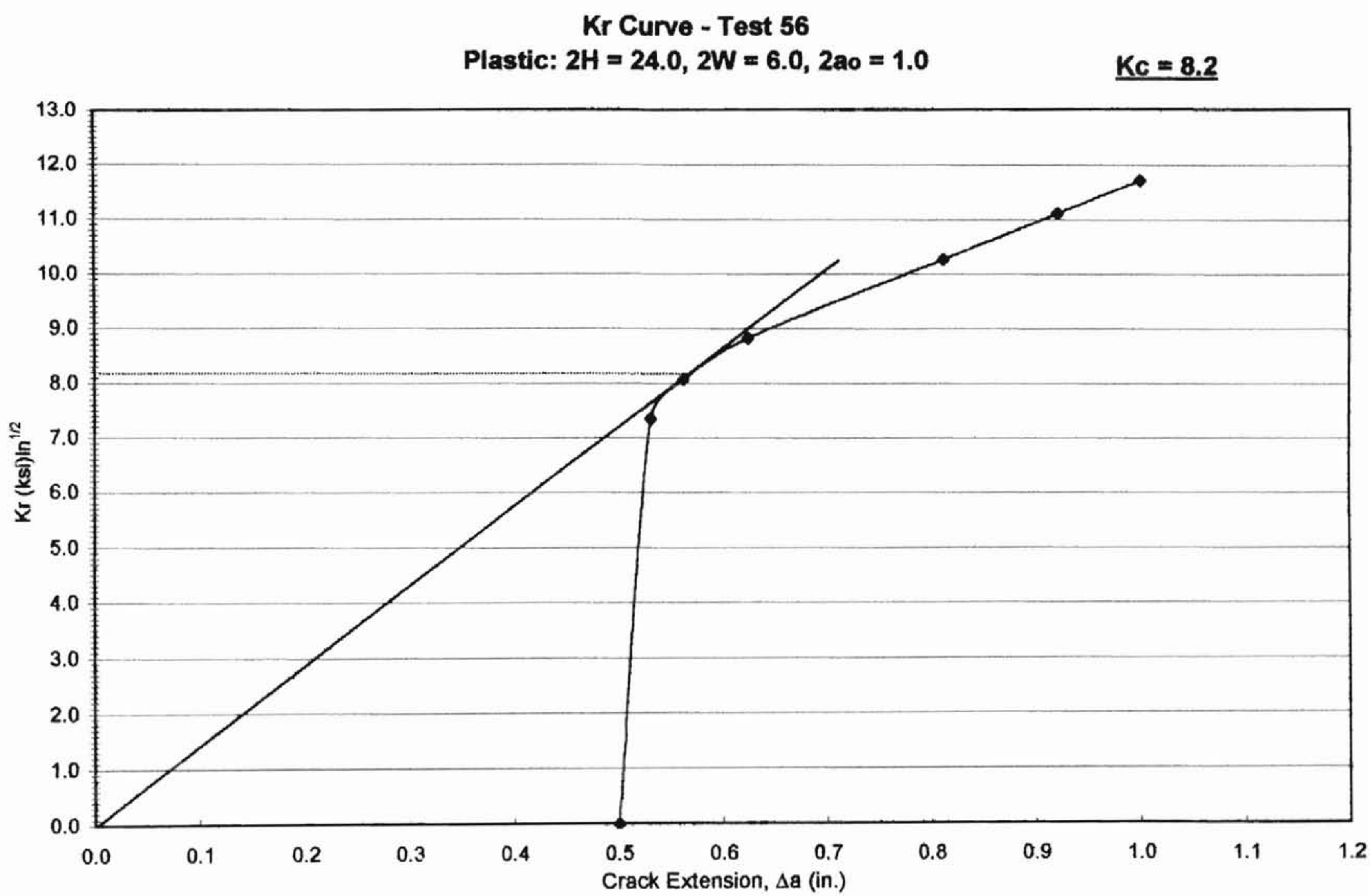

Figure 4.7.3: K_R curve for Test 56 data

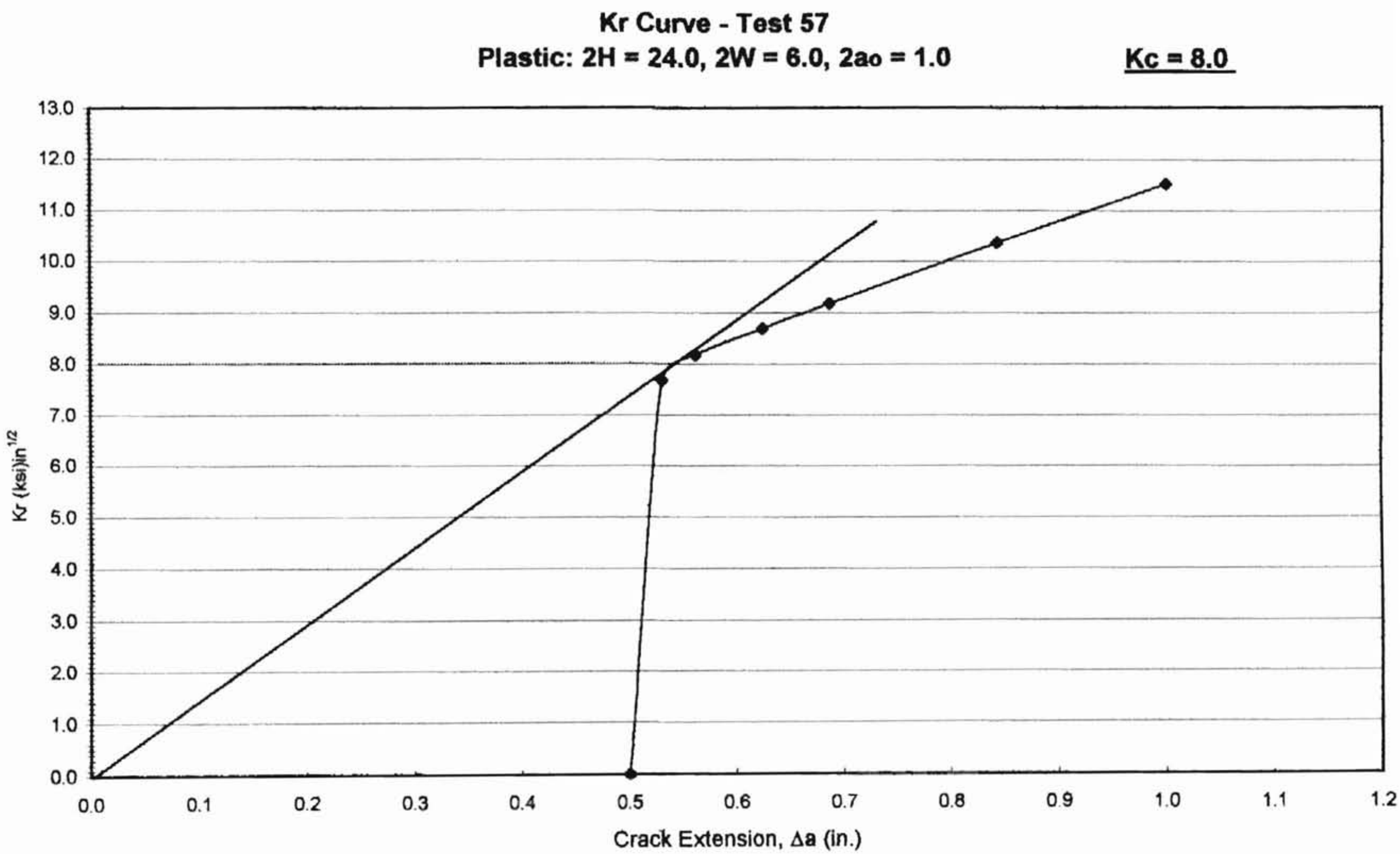

Figure 4.7.4: K_R curve for Test 57 data

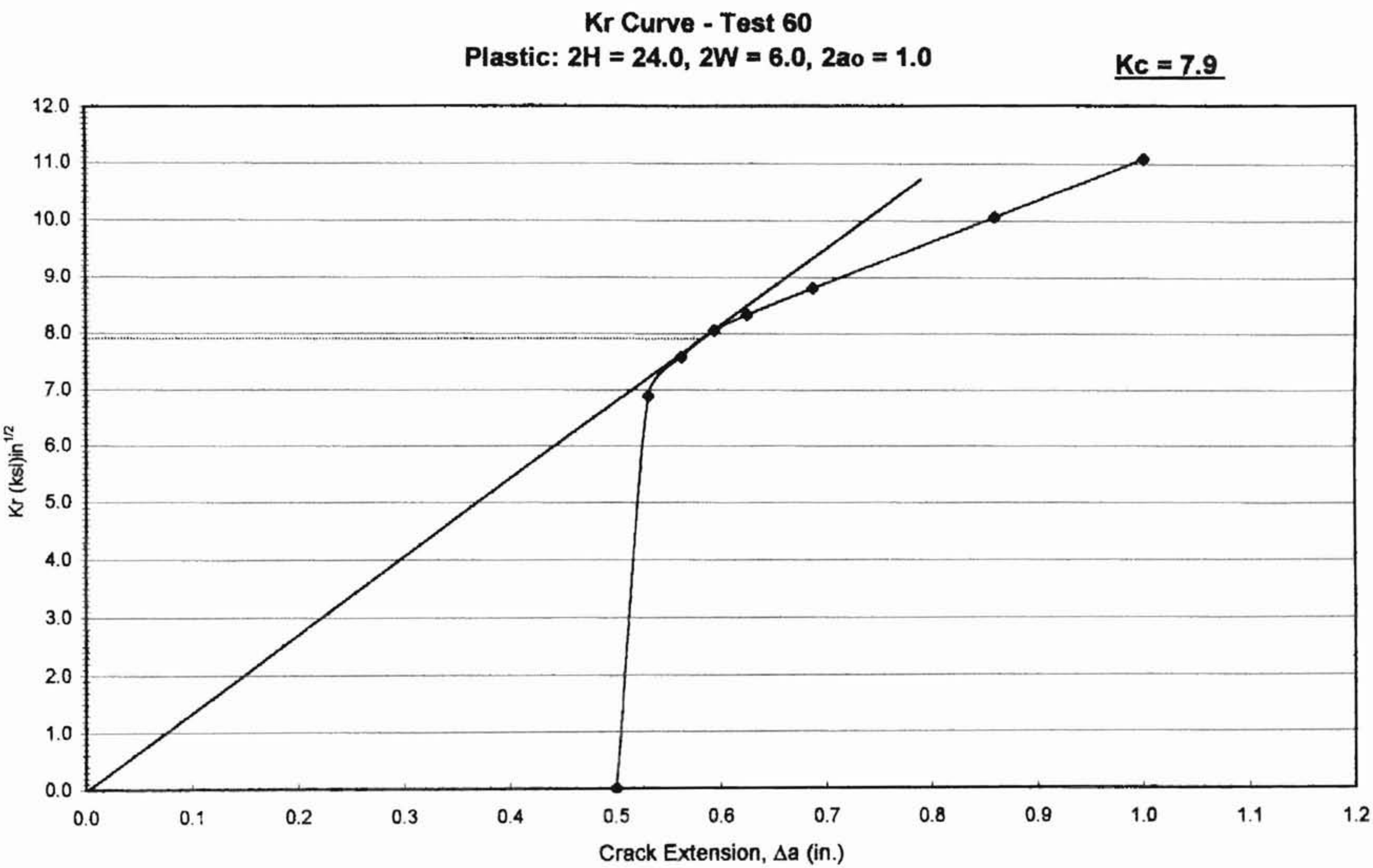

Figure 4.7.5: K_R curve for Test 60 data

Figure 4.8: K_R curves for Group 8 test runs

Group 8: Test Runs 63, 64, 65, 68

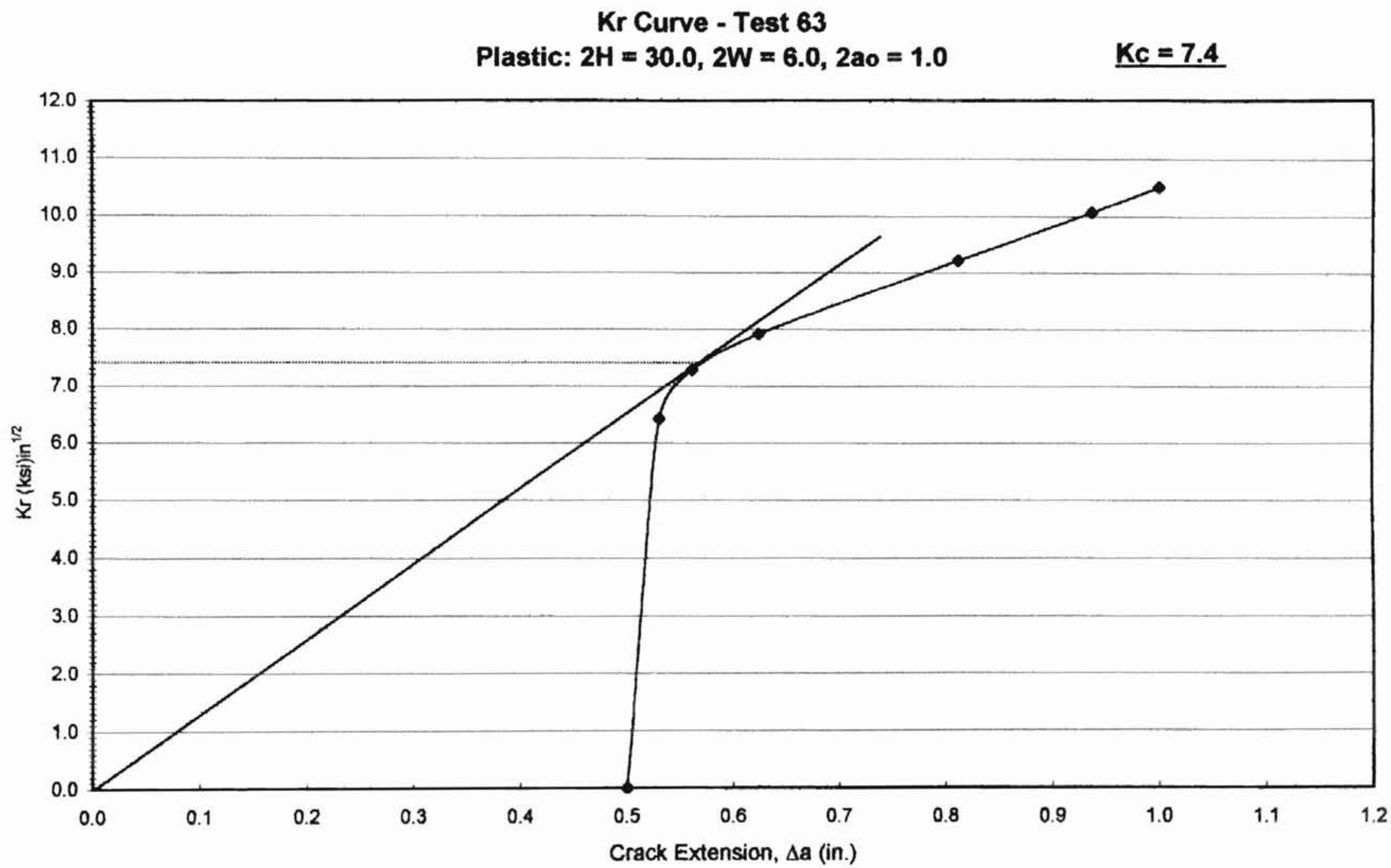

Figure 4.8.1: K_R curve for Test 63 data

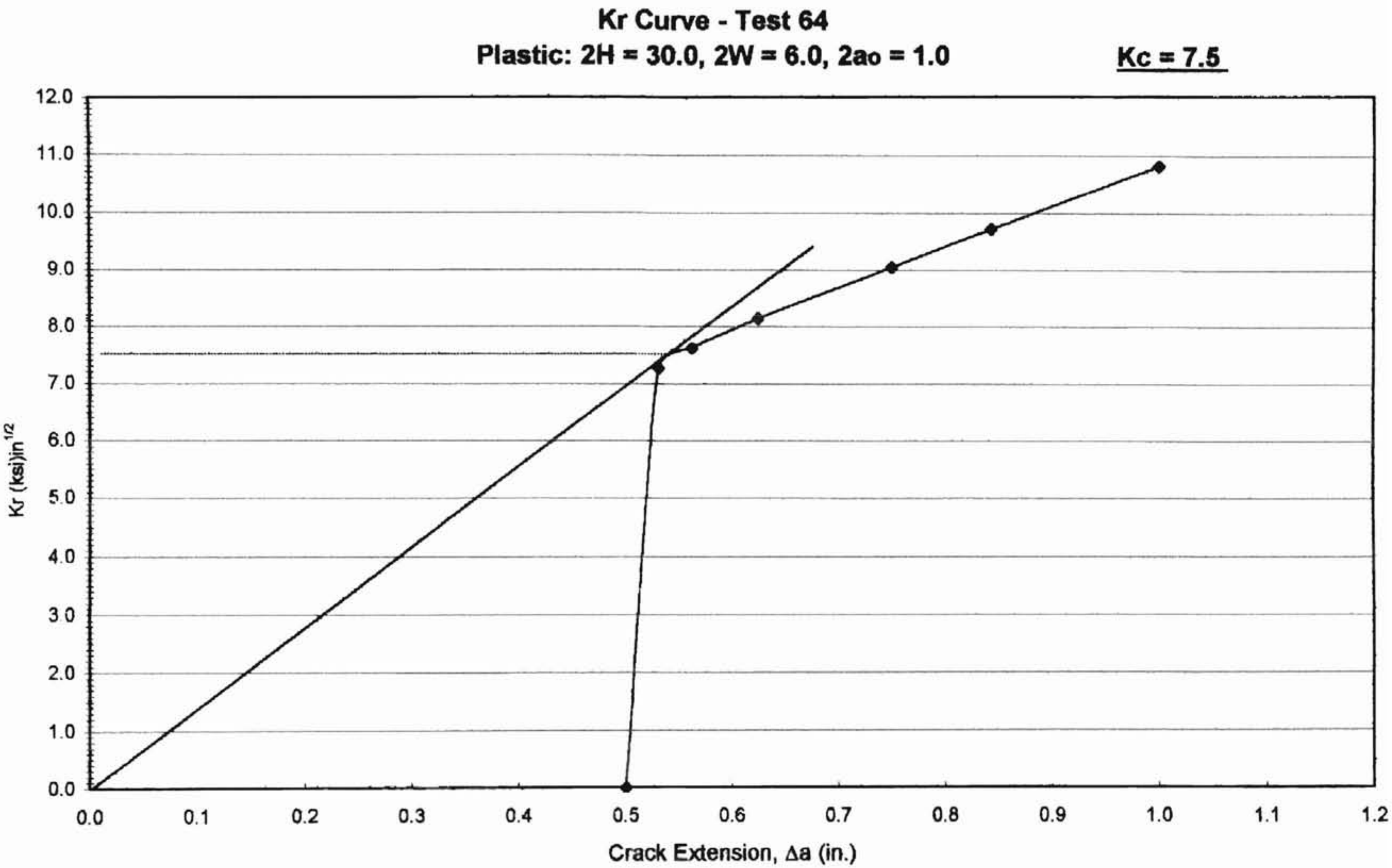

Figure 4.8.2: K_R curve for Test 64 data

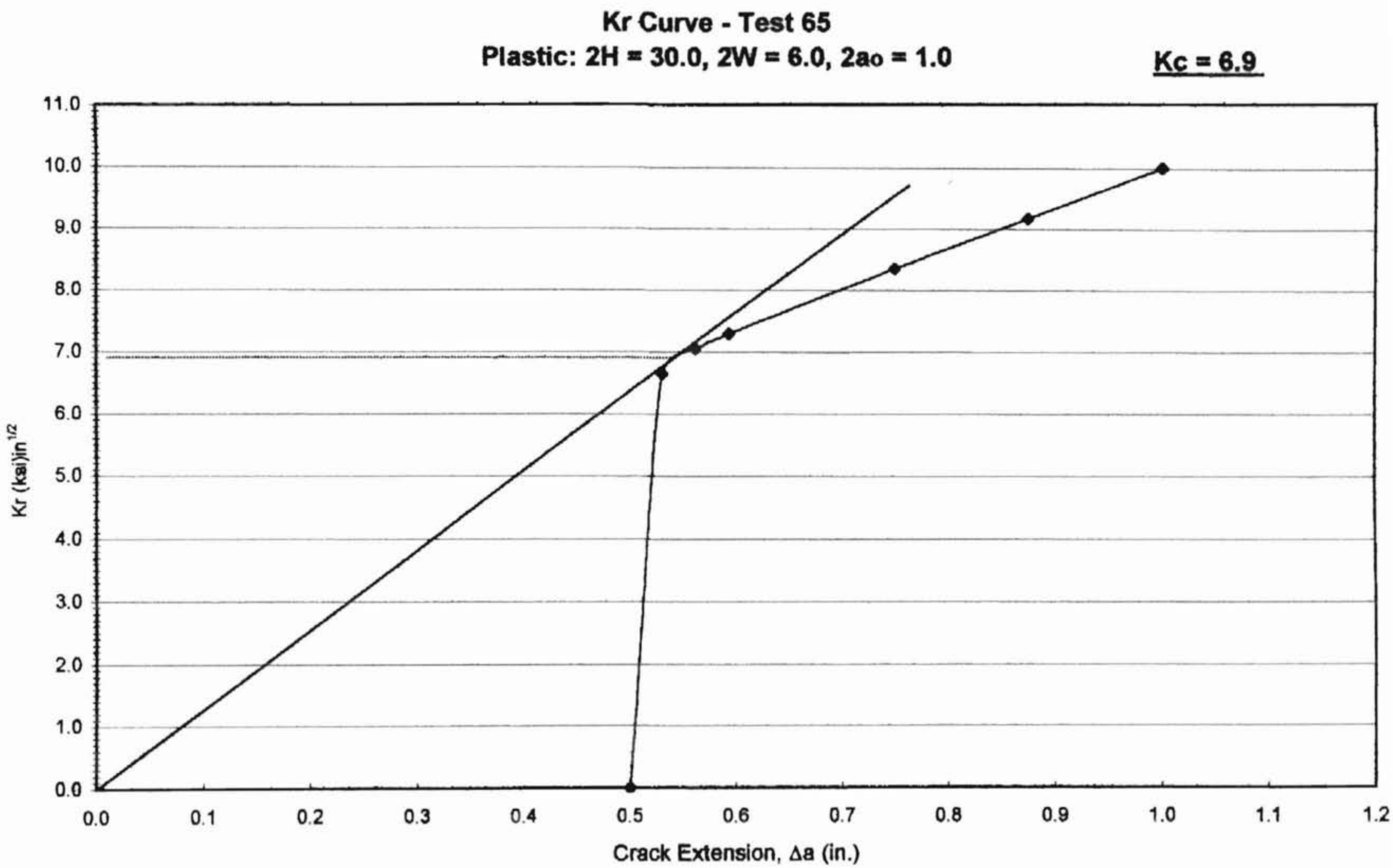

Figure 4.8.3: K_R curve for Test 65 data

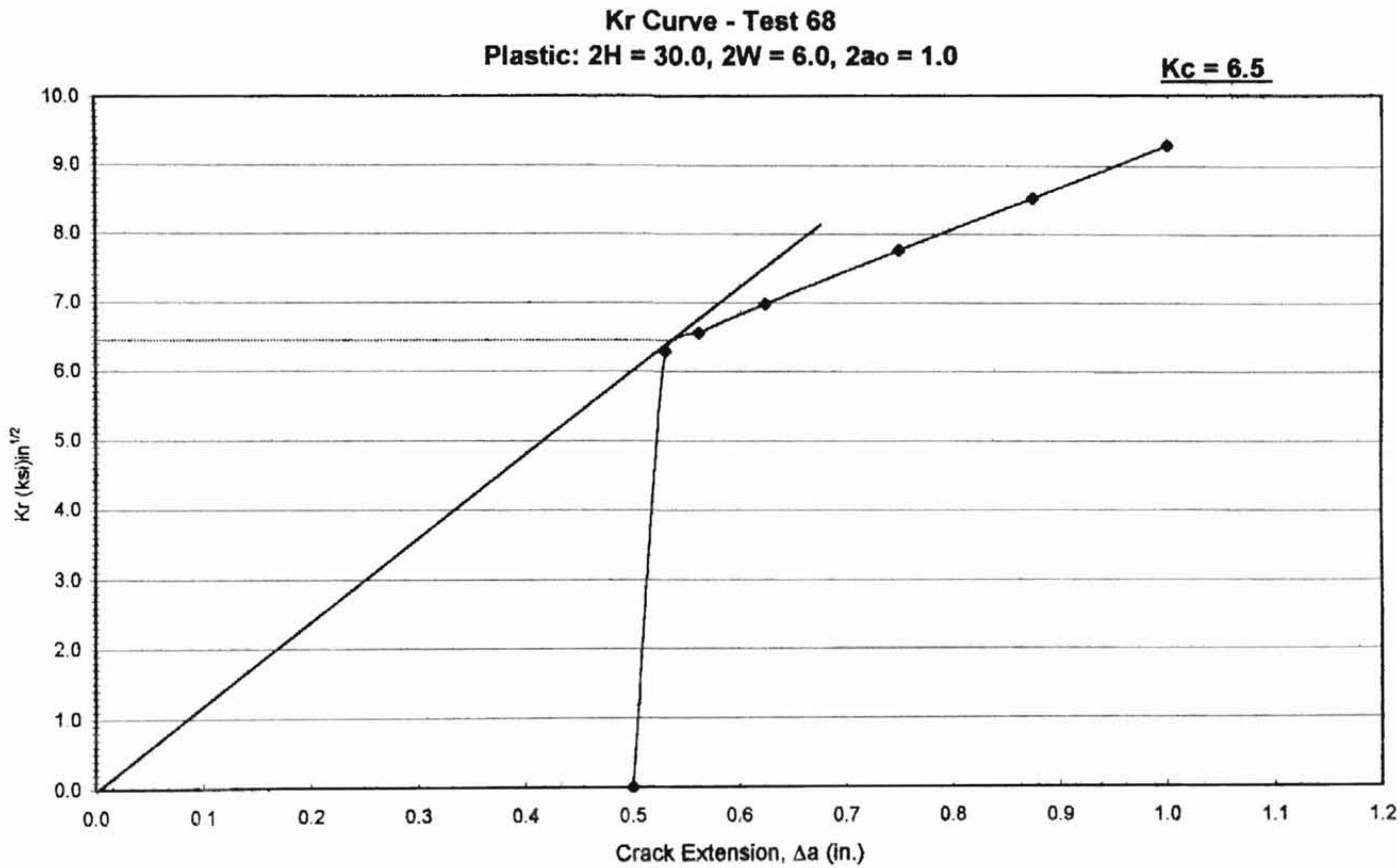

Figure 4.8.4: K_R curve for Test 68 data

4.2 Summary for Polyester Film

Table 4.1 gives a summary of the K_C values obtained from the previous figures. The table presents the group, the specimen height, the test run, the individual K_C value for each test run, and the representative average K_C value for each group.

Table 4.1: K_C [(ksi)in.$^{1/2}$] values for polyester test runs

Group 1: 2H = 0.8

TEST	K_C	AVG. K_C
10	16.2	16.2
12	16.3	
13	16.0	
14	16.4	
15	16.3	

Group 2: 2H = 0.8(Cotterell)

TEST	K_C	AVG. K_C
10	10.9	10.9
12	10.9	
13	10.8	
14	11.0	
15	11.0	

Group 3: 2H = 3.0

TEST	K_C	AVG. K_C
16	15.2	14.7
17	14.2	
18	14.4	
21	14.5	
22	15.0	

Group 4: 2H = 6.0

TEST	K_C	AVG. K_C
23	12.4	12.7
28	12.6	
31	12.7	
33	13.0	
34	12.9	

Group 5: 2H = 12.0

TEST	K_C	AVG. K_C
36	10.1	10.5
37	10.0	
38	10.7	
40	10.7	
41	11.1	

Group 6: 2H = 18.0

TEST	K_C	AVG. K_C
42	8.7	9.1
45	9.3	
46	9.7	
48	8.8	
49	9.0	

Group 7: 2H = 24.0

TEST	K_C	AVG. K_C
51	8.1	8.2
54	8.6	
56	8.2	
57	8.0	
60	7.9	

Group 8: H = 30.0

TEST	K_C	AVG. K_C
63	7.4	7.1
64	7.5	
65	6.9	
68	6.5	

The thickness for the polyester specimens is held constant at the stock value of 0.00048 inches. The width is constant for each run at 6.0 inches, and the initial crack length is held constant at 1.0 inch for reasons stated previously. The width and initial crack length are held constant to allow the K_C values to be dependent on the height change only. Now the effects of having W/H < 4 can be seen. Table 4.2 shows the K_C value associated with the W/H value for each group.

Table 4.2: Average K_C [(ksi)in.$^{1/2}$] value with respect to the W/H ratio

Group	2W	2H	W/H	Avg. K_C
1	6.0	0.8	7.50	16.2
2	6.0	0.8	7.50	10.9
3	6.0	3.0	2.00	14.7
4	6.0	6.0	1.00	12.7
5	6.0	12.0	0.50	10.5
6	6.0	18.0	0.33	9.1
7	6.0	24.0	0.25	8.2
8	6.0	30.0	0.20	7.1

Table 4.2 shows that as 2H increases, K_C decreases. This trend can be seen in Figure 4.9. Or, in terms of the width to height ratio, as W/H increases, K_C increases. This trend can be seen in Figure 4.10.

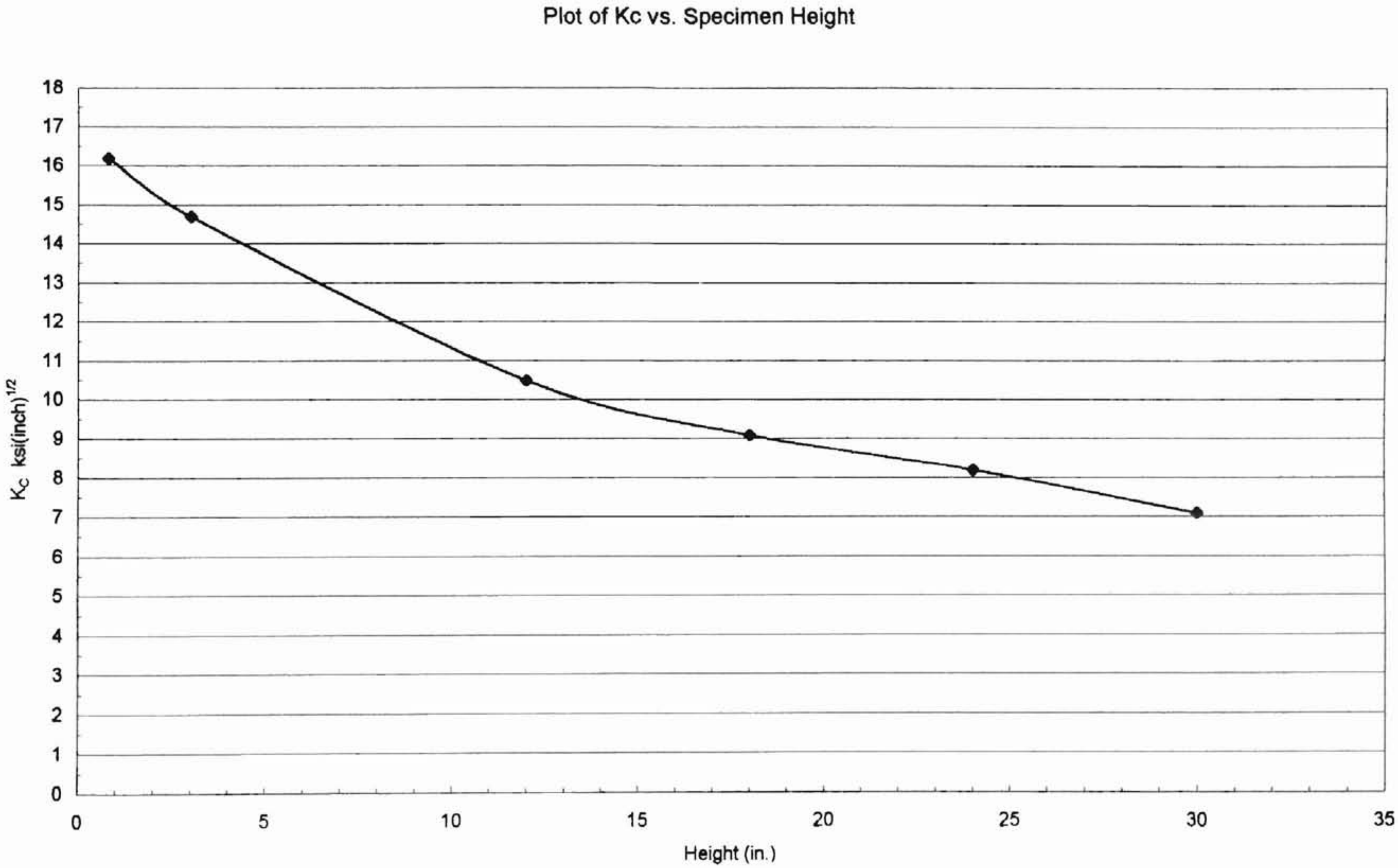

Figure 4.9: K_c vs. Height for 48 gauge polyester film

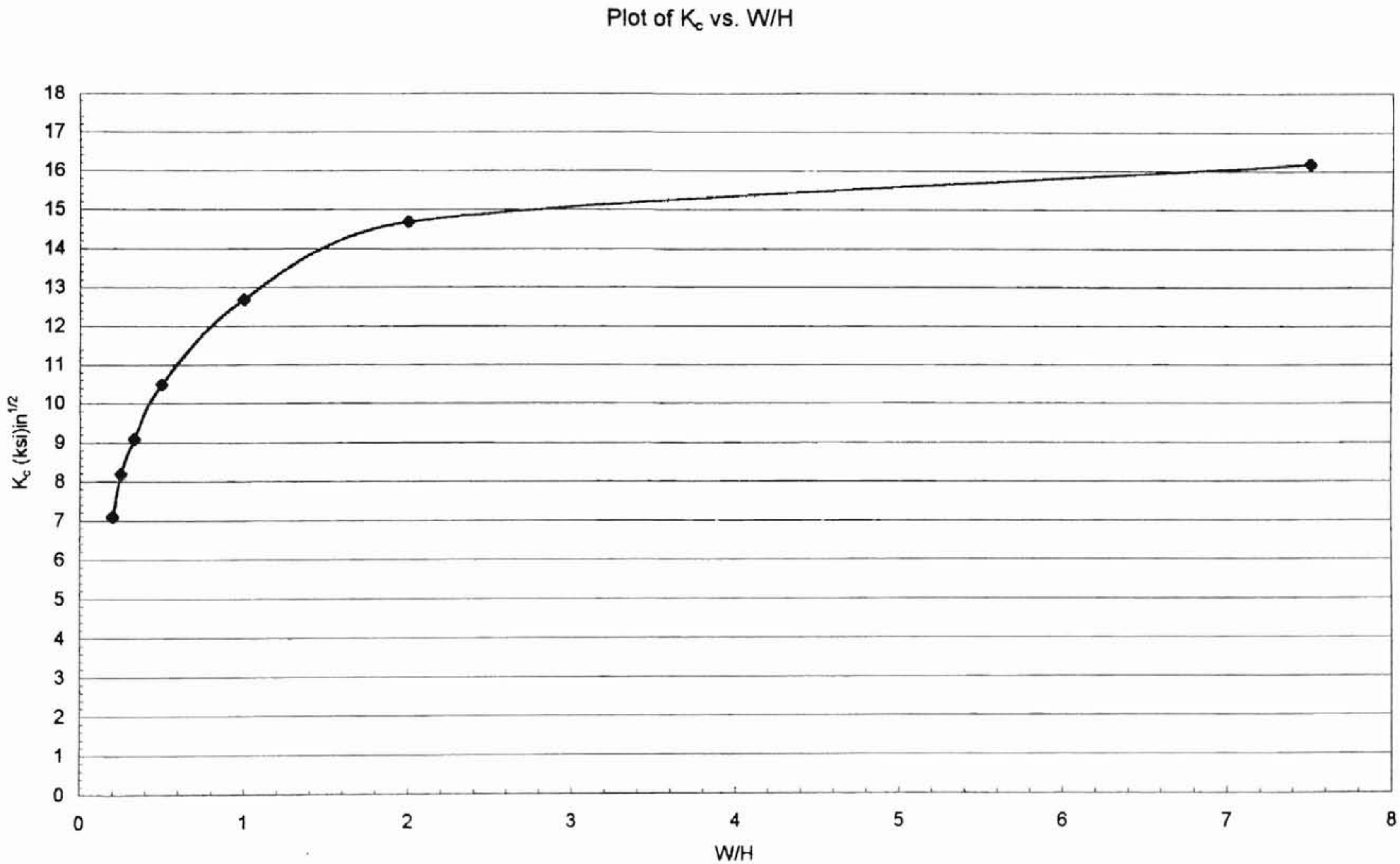

Figure 4.10: K_c vs. W/H for 48 gauge polyester film

Discussion

By studying the figures, it can be seen that in each test group the K_R curves are all consistent in appearance. Also, the spread shown in Table 4.1 for each test group is relatively small. This lends confidence to the results obtained, keeping in mind that the K_C values are to be considered representative only.

Figure 4.9 shows that as W/H decreases below 2 the K_C value begins to drop more rapidly as W/H gets smaller. The reason for this drop off is due to the presence of a more complex stress state found in the longer specimens. This more complex stress state can be attributed to the effects of out-of-plane buckling. Out-of-plane features can be seen in the test specimens starting with a height of 3 inches. The longer the specimen lengths, the more pronounced the out-of-plane features become.

Recall that the primary reason to use the CST test is to eliminate the out-of-plane buckling effects. As expected, the longer lengths allowed for great amounts of out-of-plane buckling to occur. As a result of this, K_c decreased significantly for longer height values.

The K_c value corresponding to the specimen with the minimum specimen height (0.8 inches) is over double that of the K_c value corresponding to the maximum specimen height (30 inches). If the height of the specimen could be increased past 30 inches, one might possibly see a minimum limit in the fracture toughness value. Even though an extrapolation on the data could not be performed with confidence, it should be noted from Figure 4.10 that the limiting value would approximately be 2 ksi(in)$^{1/2}$. This minimum limit K_c value would likely represent the K_c value associated with a long web span in a web handling process.

A moment should be taken here to discuss the significance of the Group 2 data set. As stated in Section 4.1, this data was analyzed using the Cotterell expression introduced in Chapter 2. It should be stated again that the Group 1 and Group 2 data are taken from the same test runs. The purpose of the Group 2 set is to compare the two equations when all validity constraints are met, i.e. at 2H = 0.8 where W/H > 4 and where $a_o > 0.8H$.

Table 4.1 shows that the average K_C value for the Group 1 data determined using Equation 3.1 is 16.2 (ksi)in.$^{1/2}$. The average K_C value for the Group 2 data using Equation 2.1 is 10.9 (ksi)in$^{1/2}$. Since all validity constraints are met, one would assume that these two expressions should give nearly identical answers. As can be seen here, this is not the case. The Cotterell Equation 2.1 was developed solely for constrained short tension test applications, therefore the K_C values obtained using this expression may be closer to actual values. The reason this expression was not used exclusively for this study is due to the fact that the $a_o > 0.8H$ constraint is met for only the 2H = 0.8 data set. Equation 3.1 has no such constraint associated with it and is considered more applicable to the longer specimen heights.

Plastic Zone Size Correction Factor

Another point that needs to be addressed is the effect the plastic zone size correction factor has in determining the plane stress fracture toughness value. The effective crack size in both Equation 2.1 and Equation 3.1 includes the edition of the plastic zone size correction factor. This factor is represented by the following equation:

$$r_Y = \frac{1}{2\pi}\left(\frac{K_{max}}{\sigma_Y}\right)^2 \quad [7] \qquad (4.1)$$

where the yield strength (σ_Y) for polyester is given as 4500 psi [8].

Taking the Group 1 data as an example, where K_{max} is 16.2 (ksi)in.$^{1/2}$, a plastic zone correction factor of approximately 2 inches would be associated with it. This correction factor is definitely not insignificant and should be included to obtain an actual K_C value. However, since the thrust of this study is exploratory and comparative, the plastic zone correction factor is not incorporated into the K_C values reported here.

Figure 4.11: K_R curves for Group 1p test runs

Group 1p: Test Runs p23, p27, p31, p35

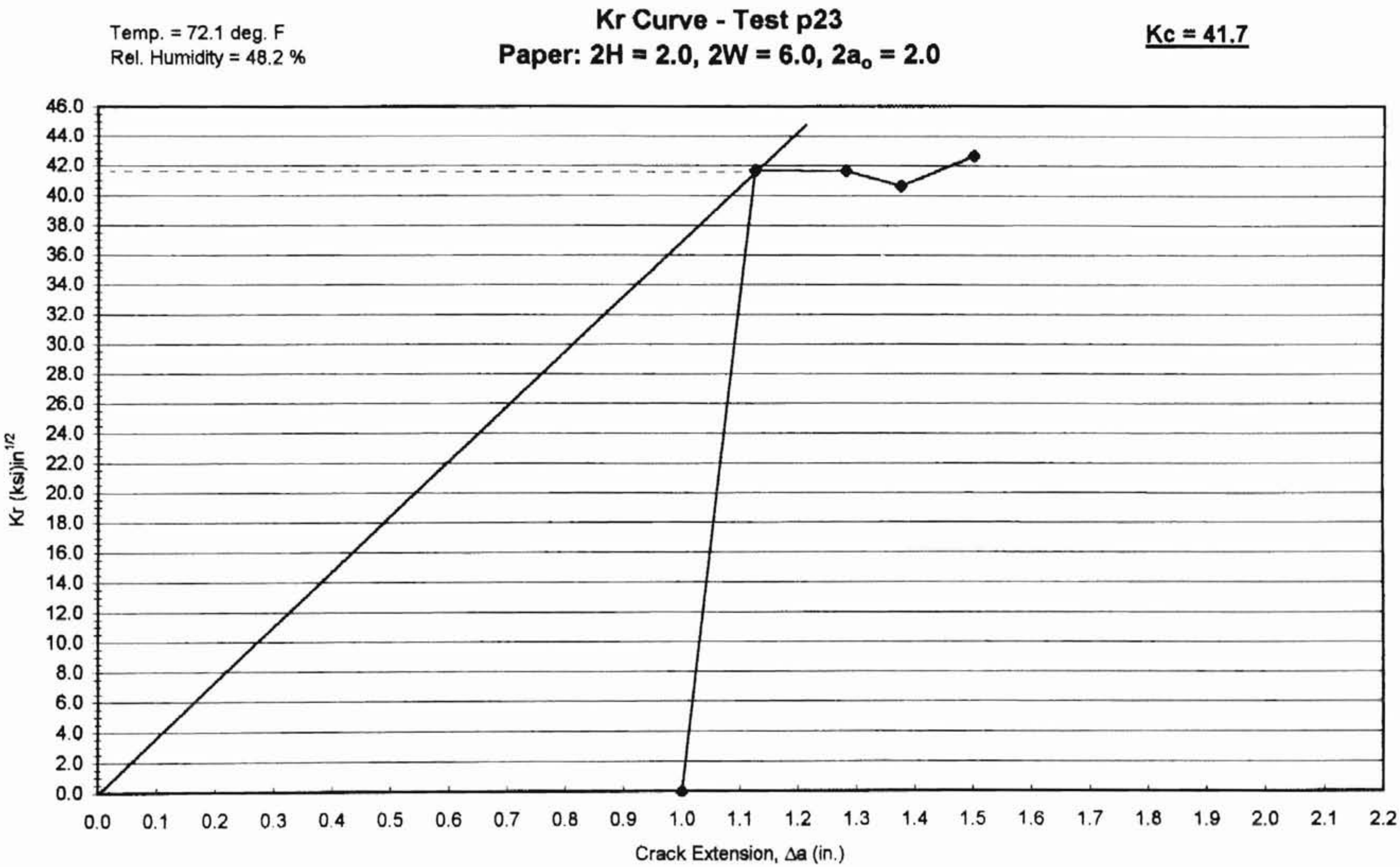

Figure 4.11.1: K_R curve for Test p23 data

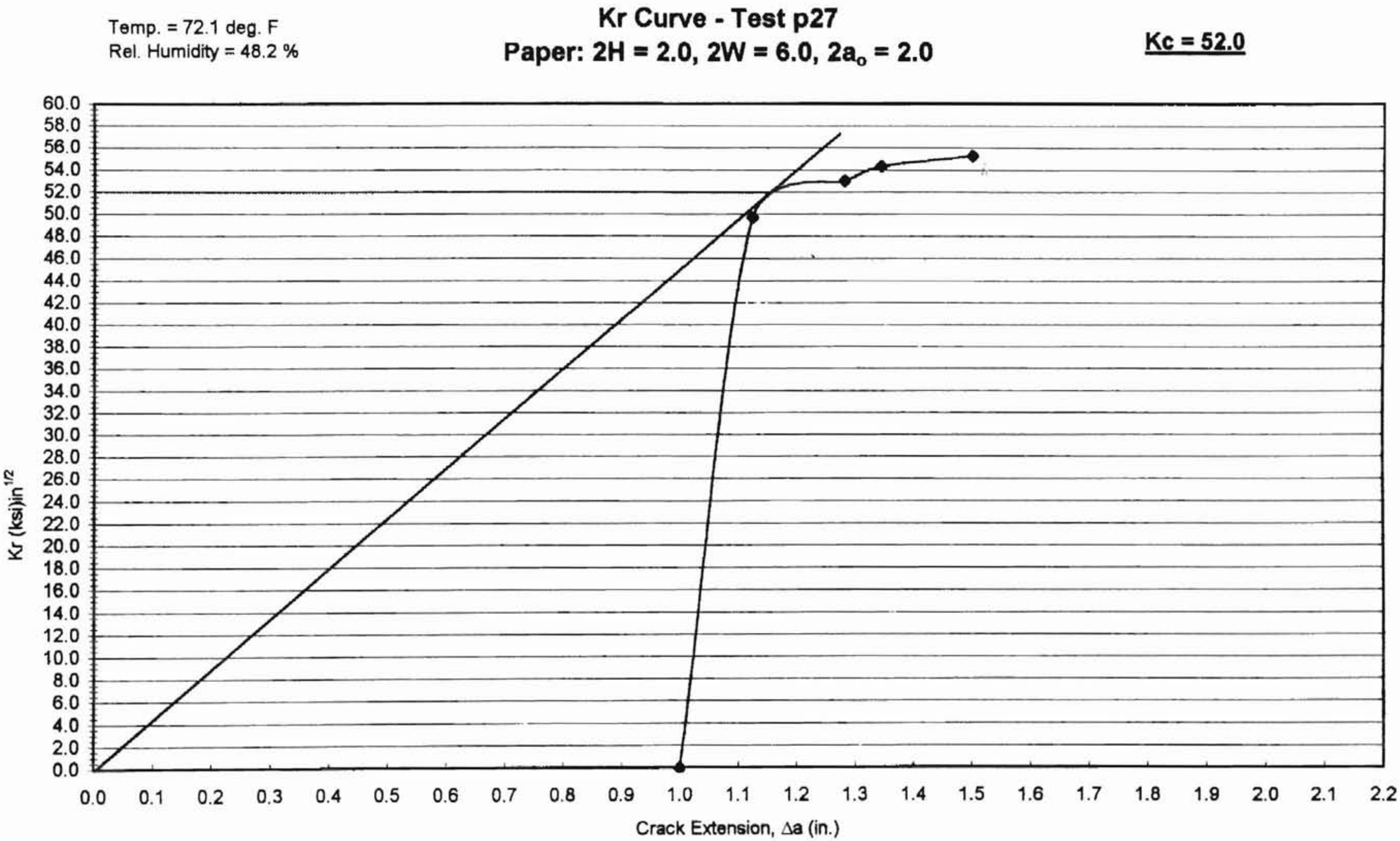

Figure 4.11.2: K_R curve for Test p27 data

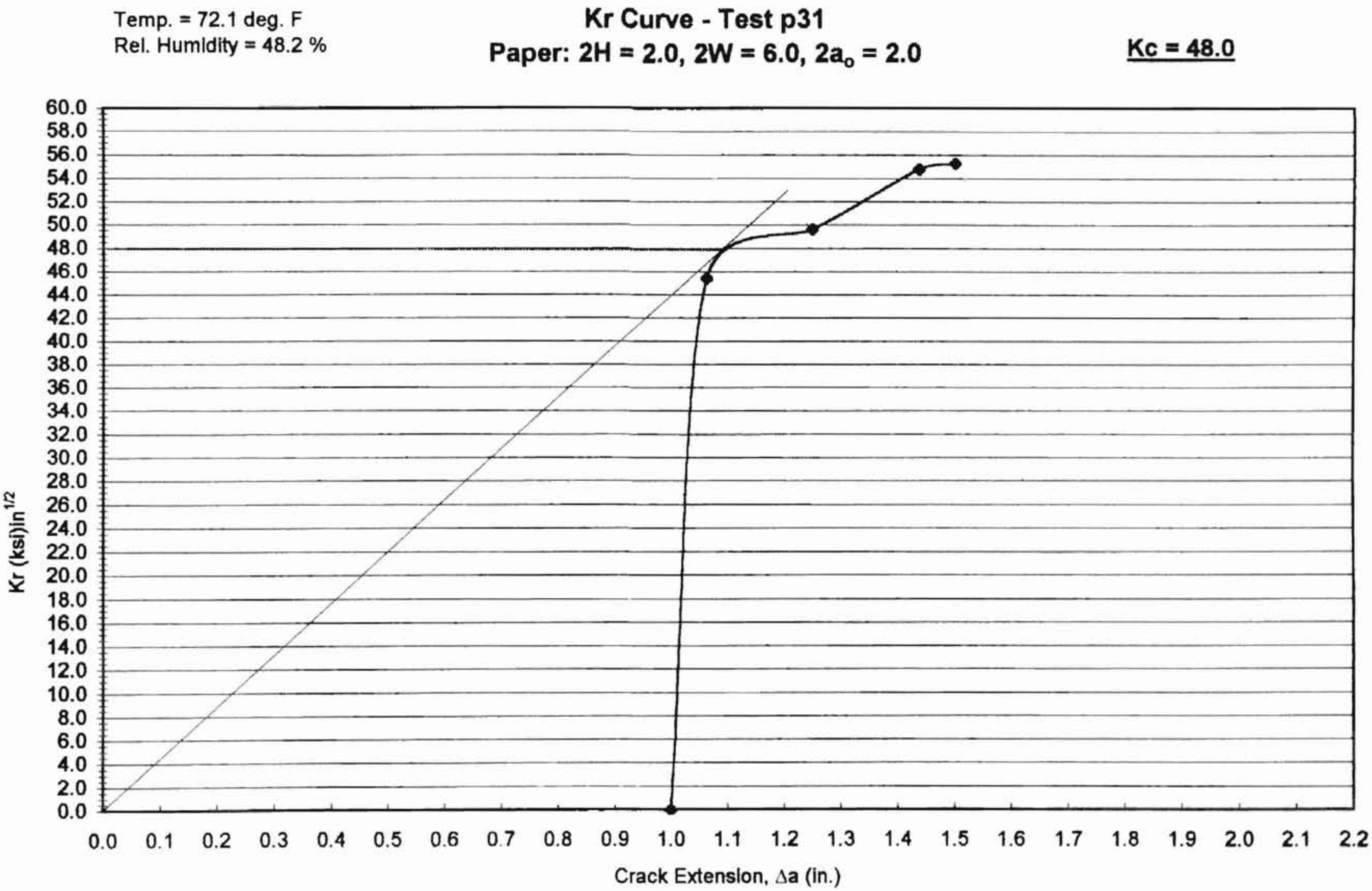

Figure 4.11.3: K_R curve for Test p31 values

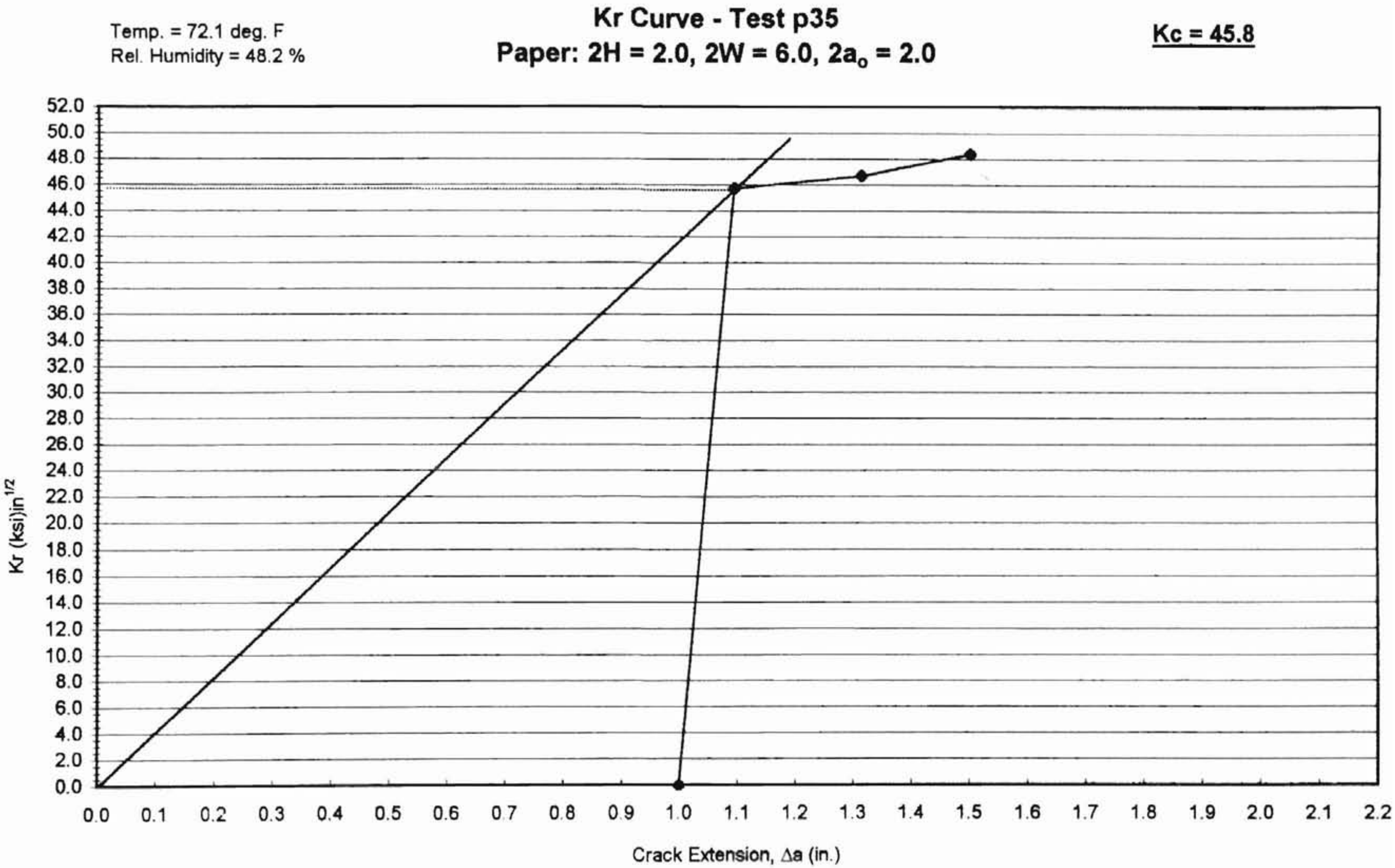

Figure 4.11.4: K_R curve for Test p35 data

Figure 4.12: K_R curves for Group 2p test runs

Group 2p: Test Runs p70, p74, p75

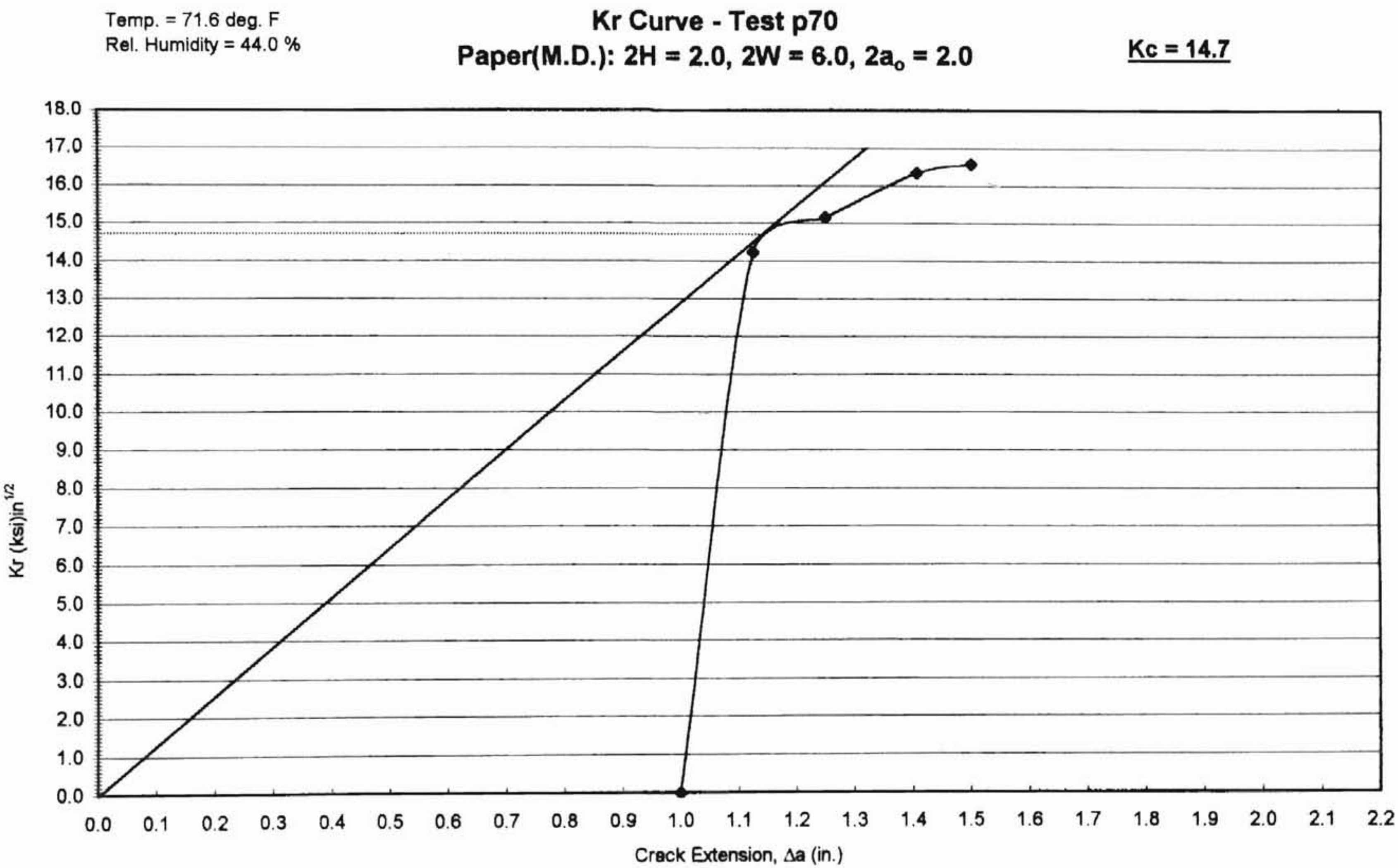

Figure 4.12.1: K_R curve for Test p70 data

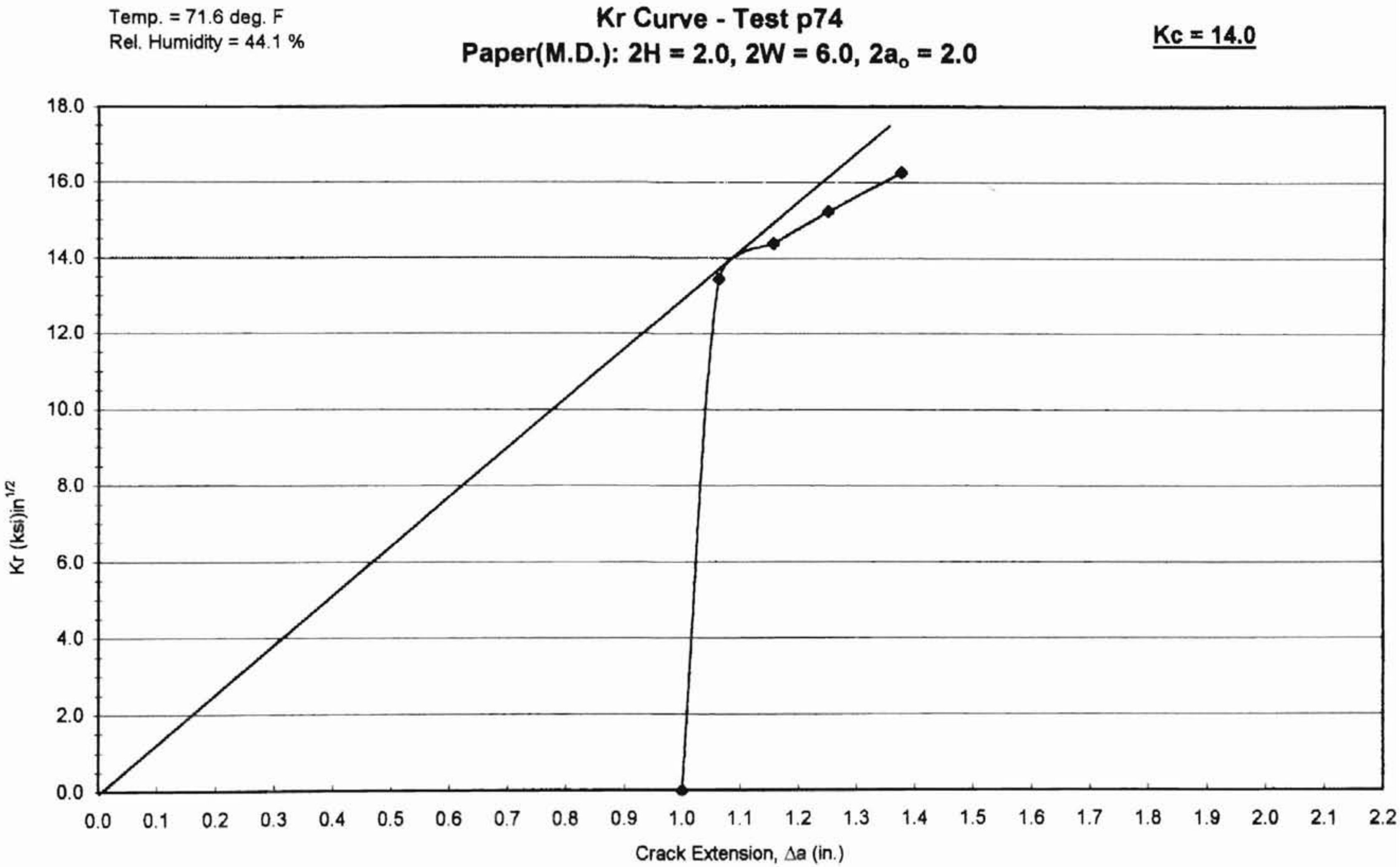

Figure 4.12.2: K_R curve for Test p74 data

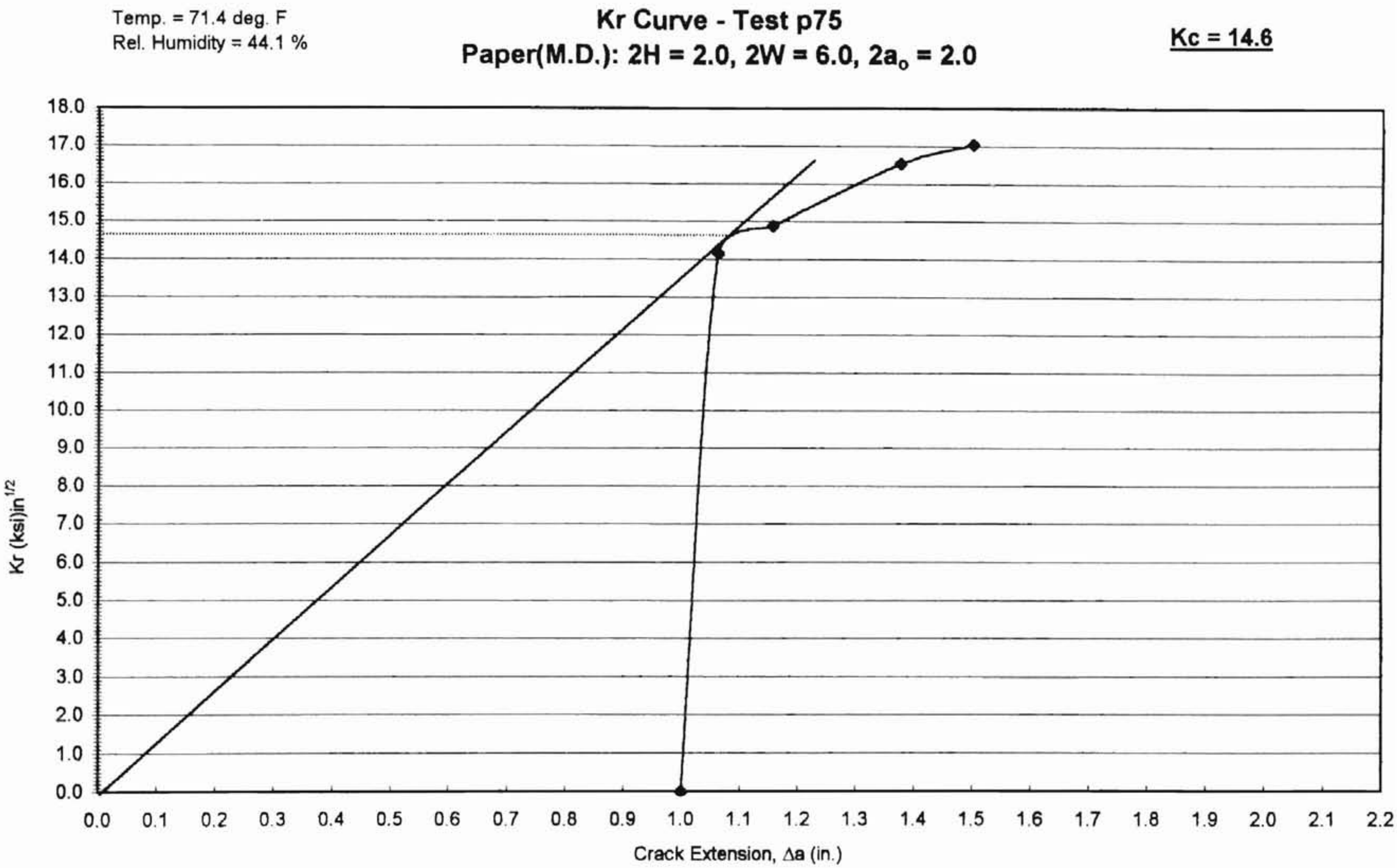

Figure 4.12.3: K_R curve for Test p75 data

Figure 4.13: K_R curves for Group 3p test runs

Group 3p: Test Runs p46, p49, p50, p54

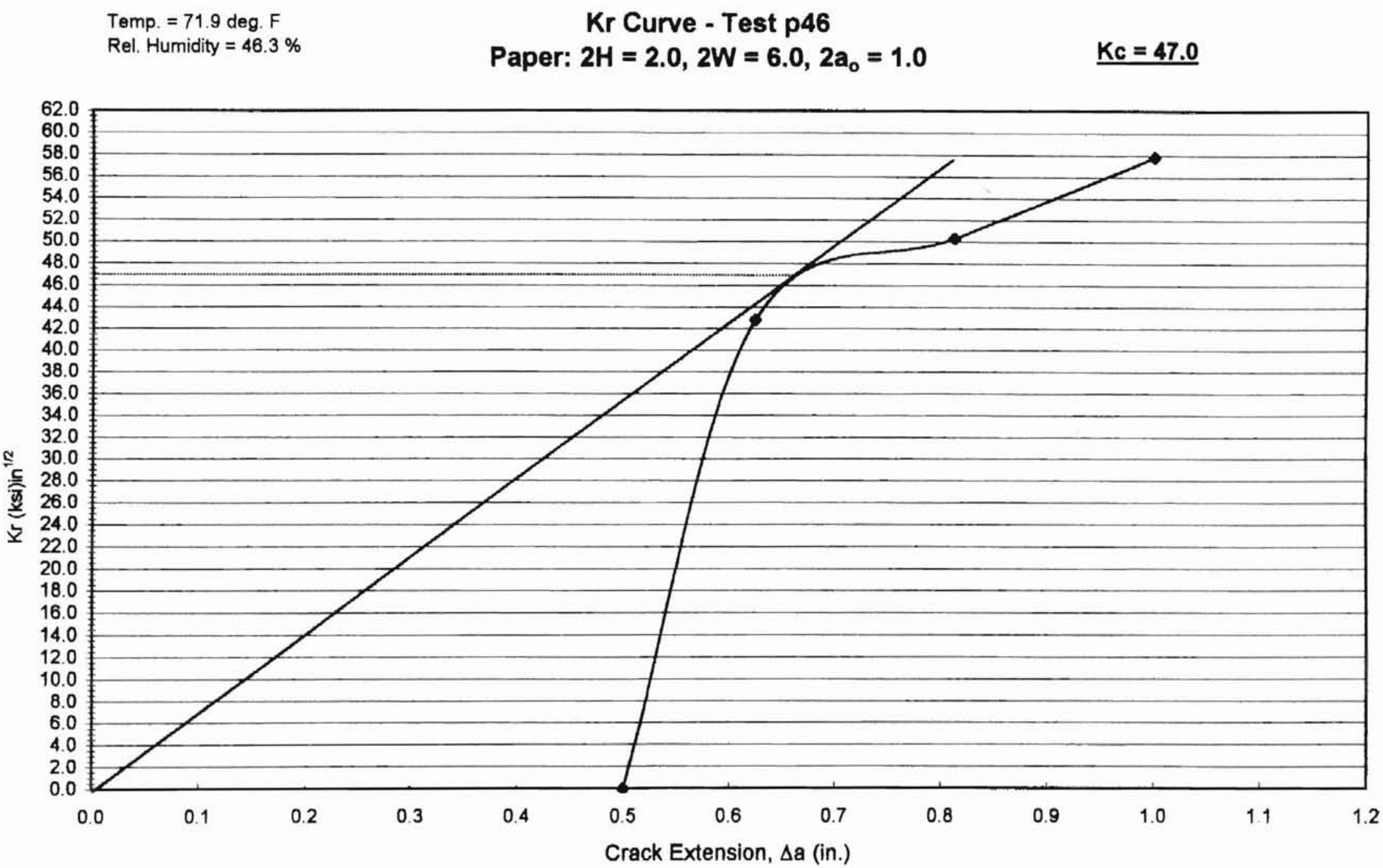

Figure 4.13.1: K_R values for Test p46 data

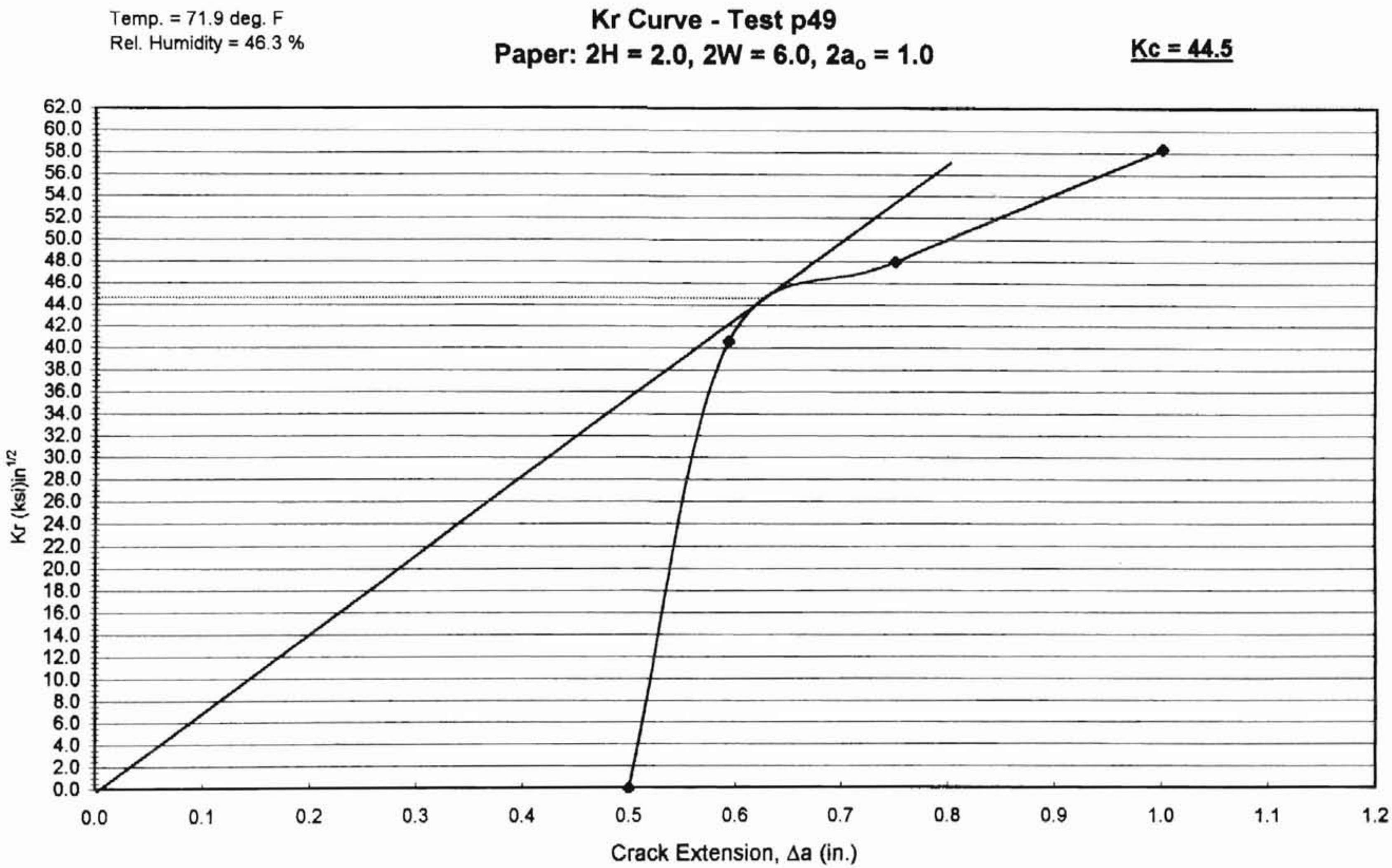

Figure 4.13.2: K_R curve for Test p49 data

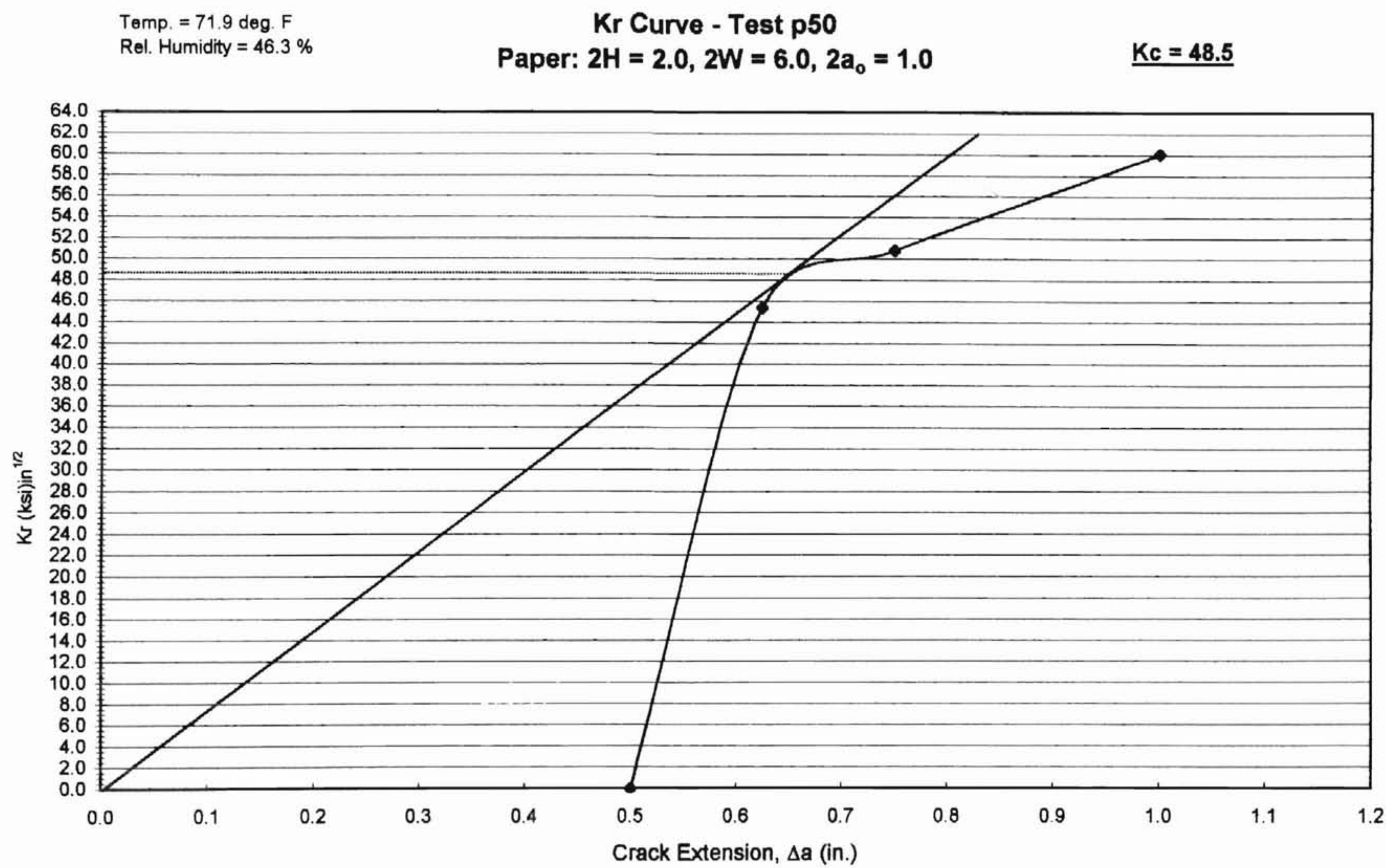

Figure 4.13.3: K_R curve for Test p50 data

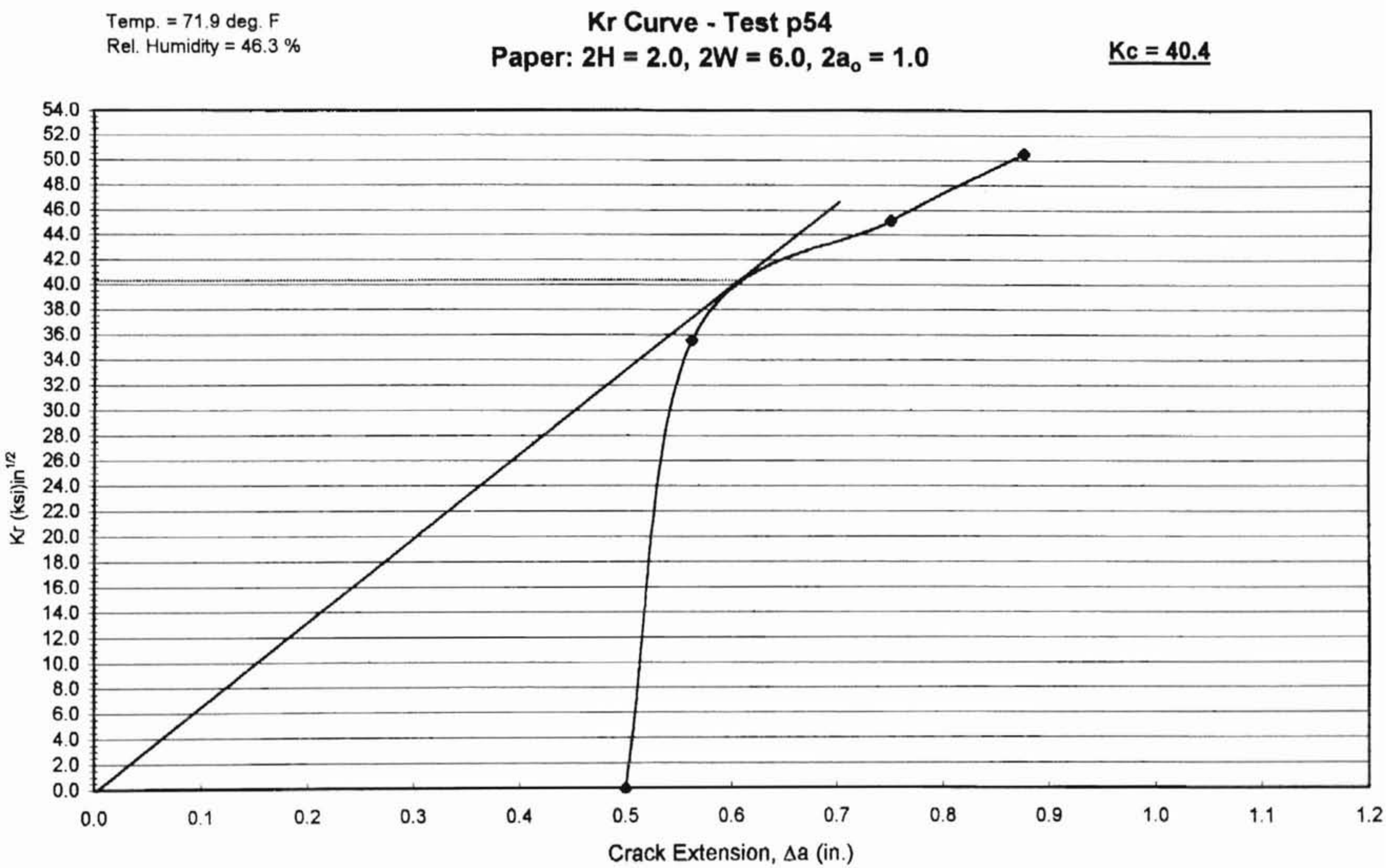

Figure 4.13.4: K_R curve for Test p54 data

Figure 4.14: K_R curves for Group 4p test runs

Group 4p: Test Runs p37, p38, p39, p42

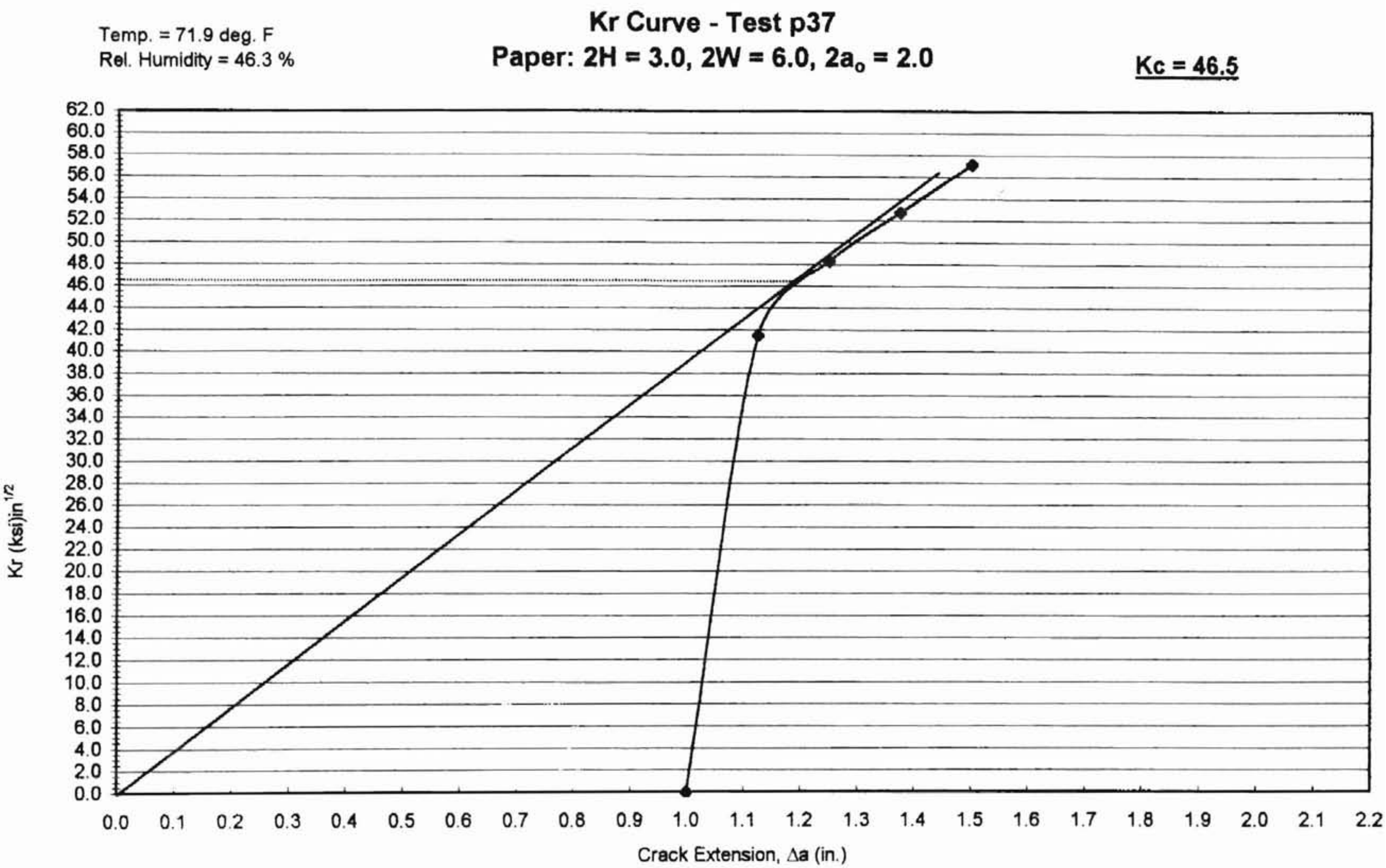

Figure 4.14.1: K_R curve for Test p37 data

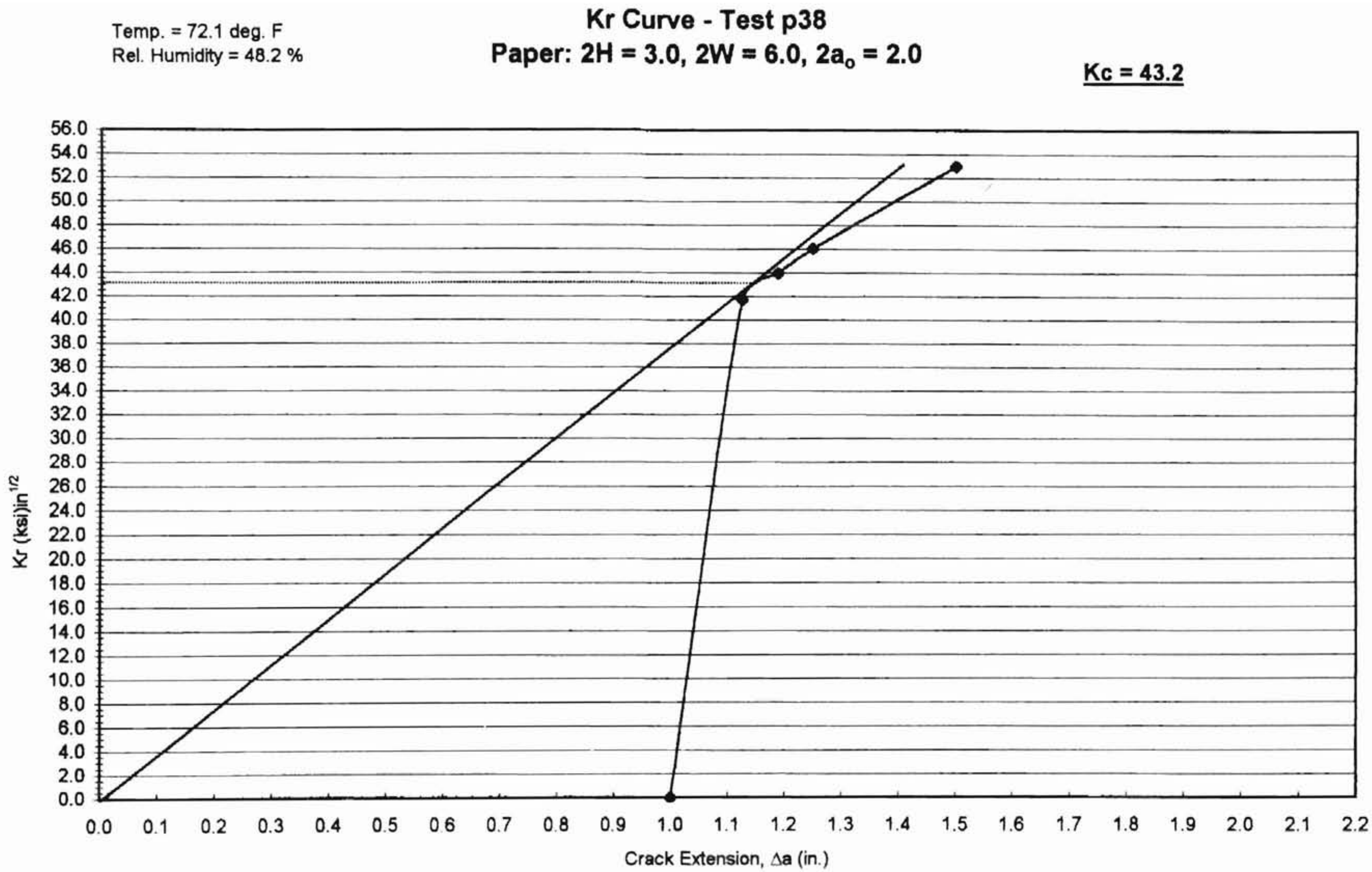

Figure 4.14.2: K_R curve for Test p38 test data

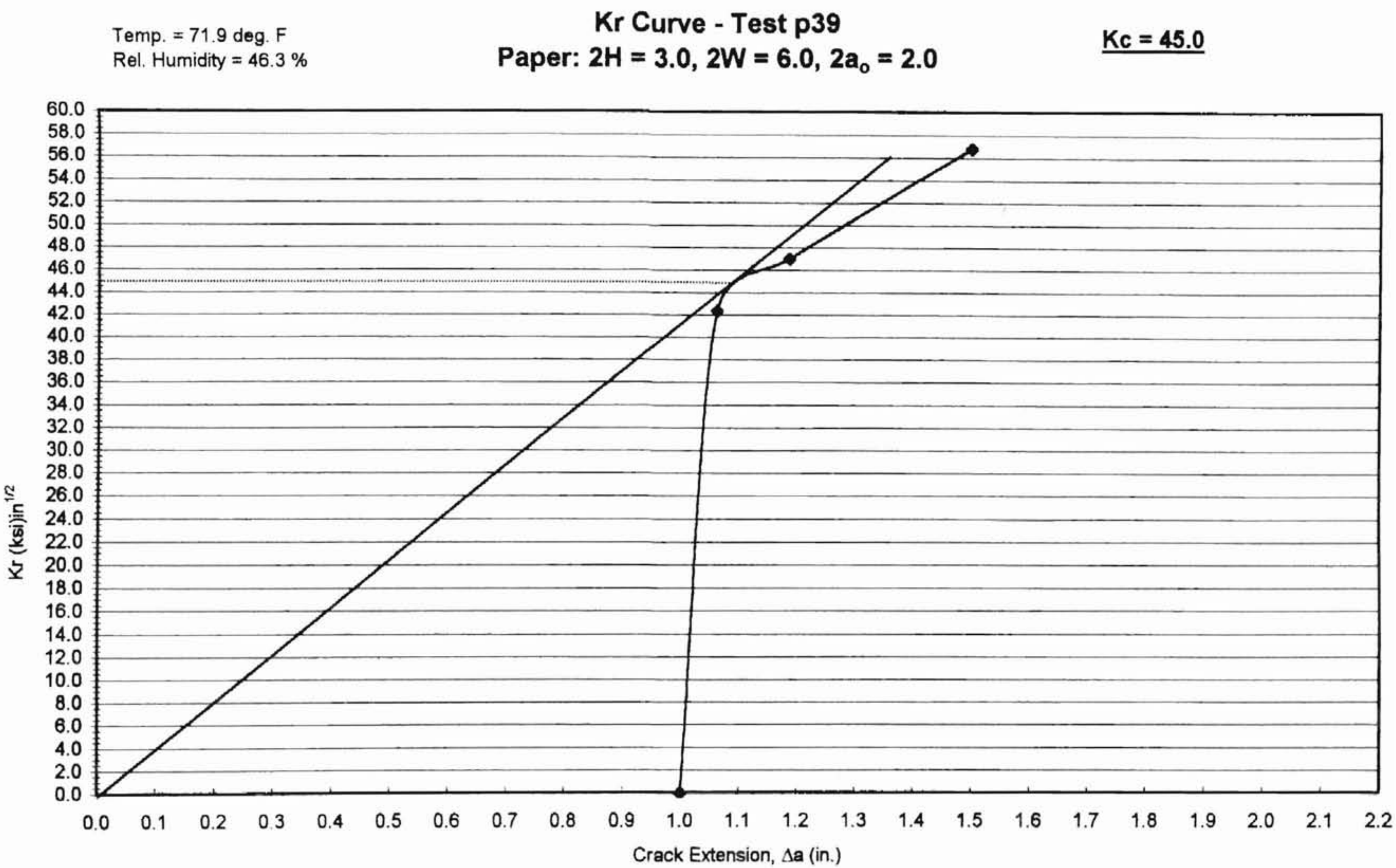

Figure 4.14.3: K_R curve for Test p39 data

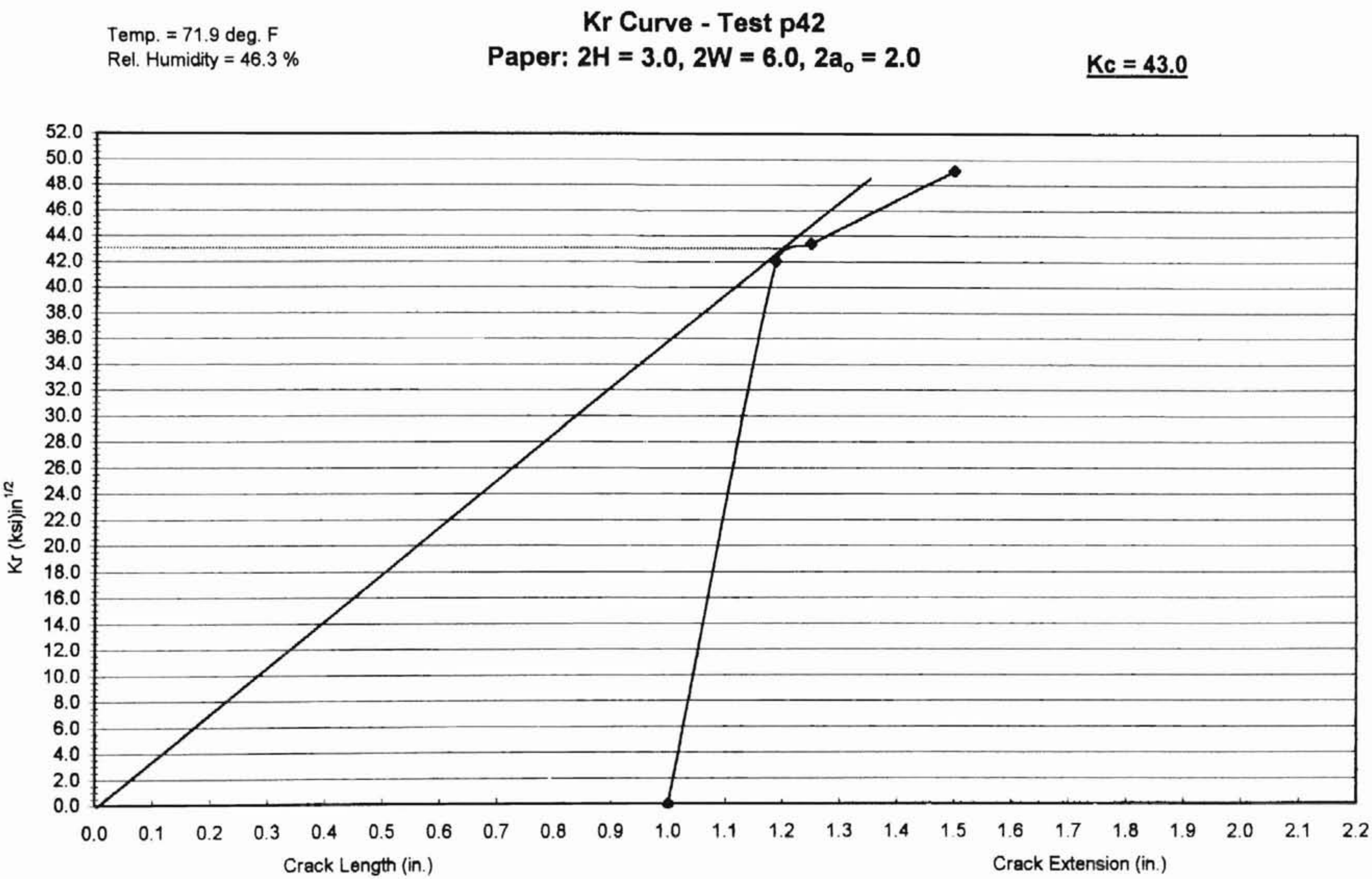

Figure 4.14.4: K_R curve for Test p42 data

Figure 4.15: K_R curves for Group 5p test runs

Group 5p: Test Runs p60, p64, p69

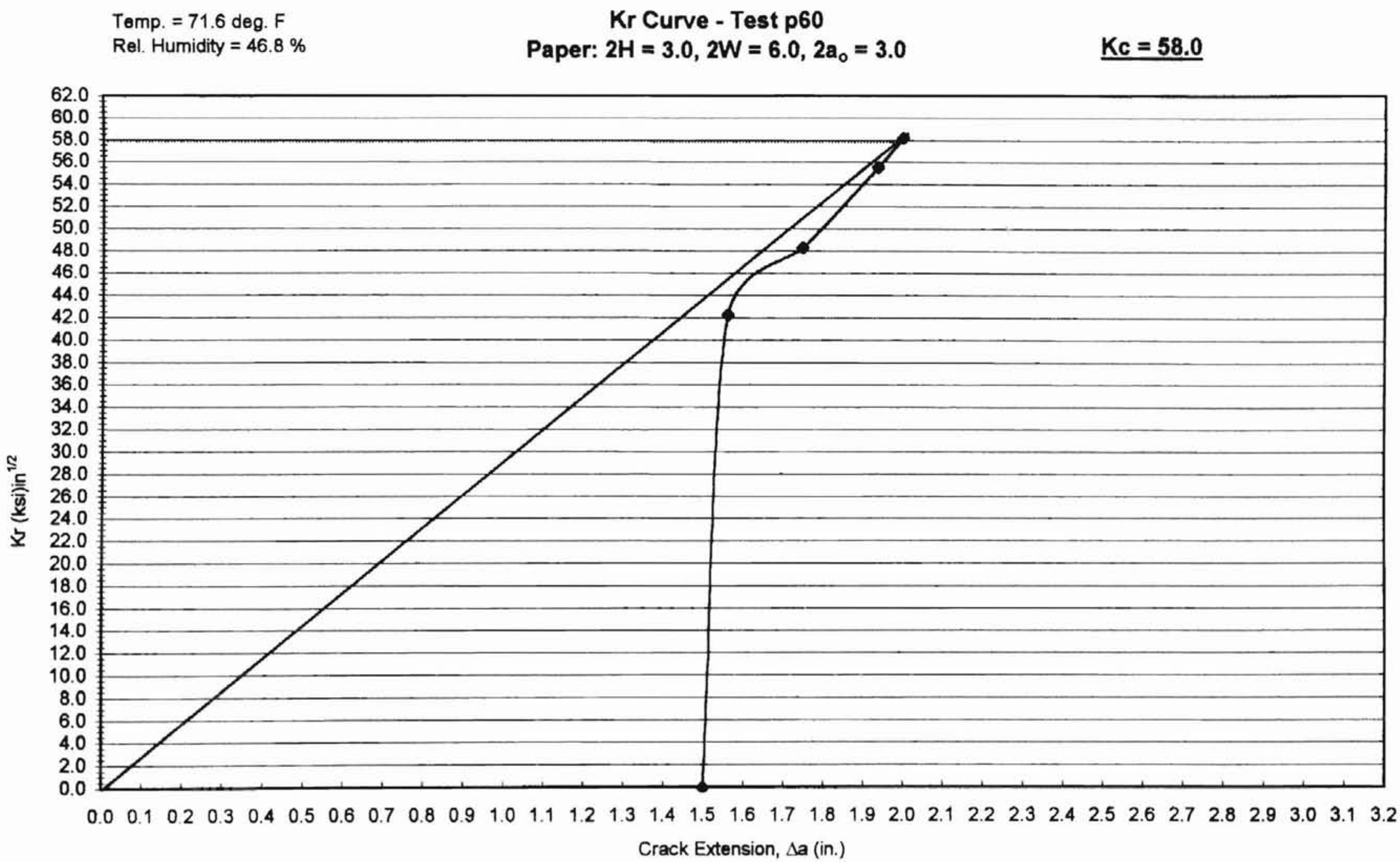

Figure 4.15.1: K_R curve for Test p60 data

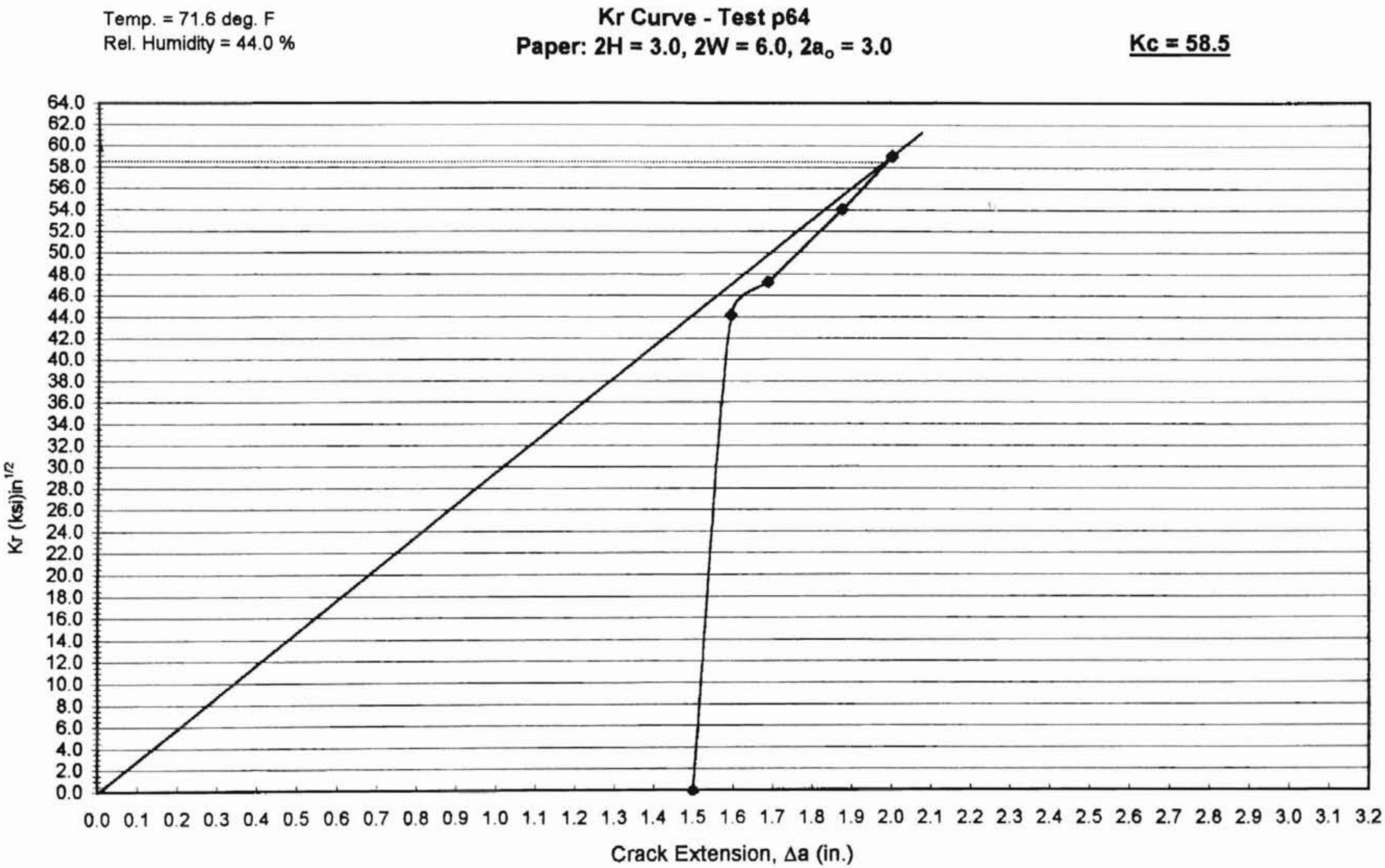

Figure 4.15.2: K_R curve for Test p64 data

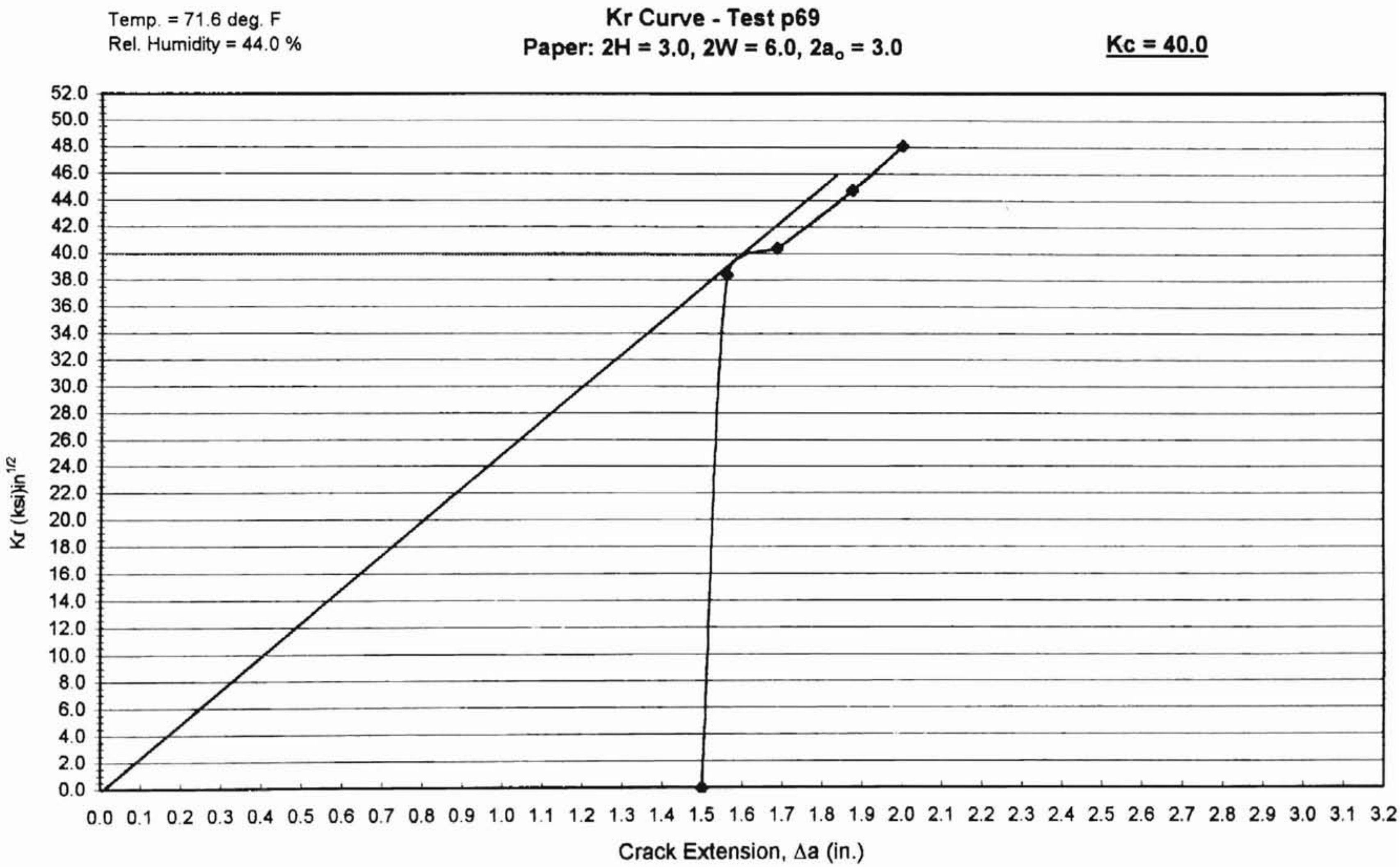

Figure 4.15.3: K_R curve for Test p69 data

4.3 Summary for Newsprint Material

Table 4.3 gives a summary of the K_C values obtained from the previous newsprint figures. The table presents the group, the specimen height, the specimen width, the test run, the individual K_C value for each test run, and the representative average K_C value for each group.

Table 4.3: K_C [(ksi)in.$^{1/2}$] values for newsprint test runs

Group 1p: 2H = 2.0, 2ao = 2.0

TEST	K_C	AVG. K_C
p23	41.7	
p27	52.0	
p31	48.0	48.6
p35	45.8	

Group 2p: 2H = 2.0, 2ao = 2.0(M.D.)

TEST	K_C	AVG. K_C
p70	14.7	
p74	14.0	14.4
p75	14.6	

Group 3p: 2H = 2.0, 2ao = 1.0

TEST	K_C	AVG. K_C
p46	47.0	
p49	44.5	
p50	48.5	45.1
p54	40.4	

Group 4p: 2H = 3.0, 2ao = 2.0

TEST	K_C	AVG. K_C
p37	46.5	
p38	43.2	
p39	45.0	44.4
p42	43.0	

Group 5p: 2H = 3.0, 2ao = 3.0

TEST	K_C	AVG. K_C
p60	58.0	
p64	58.5	52.2
p69	40.0	

The thickness for the newsprint specimens is constant at 0.00028 inches and the width is constant for each run at 6.0 inches. The thickness value is taken as a stock value.

It can be seen from Table 4.3 that as the initial crack length is increased at a given height value, the fracture toughness decreases.

Group 2p data is taken with the crack introduced in the machined direction of the newsprint material. For all other runs, the crack was introduced by cutting perpendicular to, the machined direction. As can be seen from comparing Group 1p to Group 2p in Table 4.3, the K_c value decreases significantly when the crack is introduced in the machined direction. The average K_c value for the Group 2p machined direction crack specimens is approximately 1/3 the average K_c value of the Group 1p specimens.

Discussion

One difference between the newsprint plots and the polyester plots is the fact that there are fewer data points from the onset in the newsprint. In most cases, only four data points could be established upon which to construct the K_R curves. Due to the nature of the newsprint material, much difficulty was had in observing the crack growth. The interwoven paper fibers kept the crack from opening up as much as what was observed in the polyester film. This made it difficult to get entirely accurate readings of the crack growth.

Another difference between the newsprint and polyester specimens is the resistance to crack growth initiation. As can be seen from the K_c values in Table 4.3, the newsprint has higher fracture toughness than polyester. By observing the plots, it can be seen that the newsprint also has a higher resistance to crack growth initiation. This increased fracture toughness and resistance to crack growth initiation is due to the interwoven fibers that make up newsprint.

The Cotterell Equation 2.1 was not incorporated on any of the newsprint test runs since none of the data sets met constrained conditions. As with the polyester runs, all K_C values should be considered representative.

The plastic zone in the newsprint material is considered to be negligible, therefore no correction factors need to be included in the effective crack length value.

Generally speaking, the K_R curves for the newsprint material are not as well defined as the K_R curves for polyester. This is primarily due to the fact that only a few data points were collected for each run. On average, only about 4 data points were recorded for each run. Due to the appearance of most of the newsprint curves, very little confidence is placed in the values presented. However, with improved techniques, or possibly different newsprint material, better data could be obtainable.

4.4 Unacceptable Test Runs

Many test runs were performed in the course of this study. The majority of them were unacceptable for the reasons listed in Chapter 3, Section 3.2 and discarded for the purposes of this study.

Plastic

The total number of plastic runs performed was 68. Out of these 68 runs, 34 were used. The majority of the rejections were due to one side of the initial crack growing faster than the other one. Another major factor was nonlinear crack growth. Both of these cases can be attributed to improper clamping procedures. In some cases, this could mean that the test specimen was placed in the grip plates not lined up properly. In other cases, misalignment could occur when placing the grip plates into the C-type clamps on the Instron. These two factors became even more critical at the longer specimen heights. Much care had to be taken to prevent either of these occurrences.

Paper

The total number of paper runs performed was 83. Out of these 83 runs, 18 were used. The two causes listed under the plastic section were also the main reasons for unacceptable runs occurring in the paper test runs. Another factor was the fact that the paper fibers would cause the crack to grow in an irregular, zigzag manner. The fibers also kept the crack from opening very much. This sometimes made it difficult to determine exactly when the crack started growing. In some instances, a run would have to be done again because of this. A majority of the 83 runs performed for paper were experimenting with the different size considerations. For the reasons listed, the geometries listed in the data collection were the only ones that gave acceptable runs with the current test configuration.

CHAPTER FIVE

CONCLUSIONS

Polyester

1. The plane stress fracture toughness value of polyester for W/H > 4 is in the range of approximately 11 to 16 (ksi)in.$^{1/2}$ depending on whether Equation 2.1 or Equation 3.1 is more applicable.
2. When W/H becomes less than 4, but is in the range of 2 to 4, K_C values drop gradually. This is due to the small buckling contributions that are present.
3. When W/H falls below 2, the K_C value decreases more rapidly. Buckling contributions have a larger effect in this range.
4. Long web spans appear to have approximately 1/8 the K_C value of the constrained condition.

Paper

1. Crack initiation is difficult to detect in newsprint due to the fiber make-up of paper. The fibers also make data collection as a whole more difficult than polyester runs.
2. Cracks introduced in the machine direction produce K_C values that are approximately 1/3 that of cracks introduced in the cross-machine direction.
3. Current testing techniques gave acceptable test runs only when W/H was less than 4. Therefore no valid K_C values could be determined by current methods.

General

The first part of this study shows that standard CST fracture test methods that use the established criteria to obtain "valid" plane stress fracture toughness values do not necessarily represent conditions that occur on long web lines. According to the findings here, long web lines would see a lower fracture toughness value than what would be reported by using standard testing criteria.

The second part of this study shows that it is possible to use the CST method to get plane stress fracture toughness data for newsprint or paper media. However, the method needs to be refined to get better crack growth readings and valid K_c values.

CHAPTER SIX

FURTHER WORK

Further work in modifying or improving the current test method may allow for better testing of newsprint, or paper, media. Focus should definitely be placed on improving the grips. Currently, there are many minute factors that can greatly affect the reliability and consistency of testing. Alternate methods of recording crack growth data should be investigated also. The method employed in this study was accurate to a certain degree, but much greater accuracy should be obtainable, possibly with a more technical approach to the problem. Also, wider newsprint specimens should be tested so that the $W/H > 4$ criteria can be met and valid results achieved.

Further work in the area of polyester testing should involve the effects that orientation has on the plane stress fracture toughness value. For this study, all tests were run with the crack introduced in the cross machine direction. Testing should also be done with cracks being introduced in the machine direction in specimens of varying height and width.

Another area not expanded upon in this study was the area of thin metal sheets or shim stock. With the modifications and improvements mentioned above, thin metal specimen testing should be obtainable using this method.

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VITA

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Master of Science

Thesis: STUDY OF DIMENSIONAL EFFECTS IN CONSTRAINED SHORT TENSION OF PLANE STRESS FRACTURE TOUGHNESS TESTS FOR POLYESTER FILM AND NEWSPRINT

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