# Fracture Toughness and Fracture Surface Morphology of Cold Forging Die steels

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**Keywords:** Fracture toughness, Three point bending, Crack initiation energy, Charpy impact energy, Cold forging die steels, Unstable fracture, Stretched zone

**Abstract.** In this paper the emphasis is placed upon fracture toughness and fracture surface morphology of cold forging die steels with Rockwell C scale hardness number of 52 to 68. Three point bending fracture toughness tests were conducted by use of Charpy impact specimens with fatigue crack for ten kinds of cold forging die steel. The higher the hardness the lower the fracture toughness is. The fracture toughness and crack initiation energy are well correlated to hardness. The Charpy impact energy of 5mm Unotched specimen, 2.5mm saw cut specimen and 2.5mm saw cut specimen with fatigue crack is also well correlated to hardness. Well defined stretched zone was observed between fatigue and unstable fracture surface of SKD61 steel with Rockwell C scale hardness number with 52, ill defined stretched zone was observed on fracture surfaces of harder steels such as cemented carbide. It can be concluded that the relation between stretched zone width and fracture toughness can be expressed as $SZW(\mu m)=3.28(Kc/\sigma_y)^{1.24}$ for structural materials including cold forging die steels in the range of SZW between150 $\mu$ m and 0.5 $\mu$ m.

## Introduction

The cold forging die failures are caused by inadequacy of variables such as die materials, die design, die manufacturing and forging operations. Cold forging dies most frequently fail brittle from fatigue crack initiated at stress concentrated area. In order to prevent die failure and to improve die life it is necessary to evaluate fatigue and fracture behavior of cold forging die steels. However not so many papers could be found on fatigue and fracture behavior of cold forging die steels with Rockwell C scale hardness number of 52 to 68. Authors have already presented on low cycle and giga cycle fatigue behavior of cold forging die steels[1,2,3]. In this paper three point bending fracture toughness testing results are presented for ten kinds of cold forging die steel with Rockwell C scale hardness number of 52 to 68. Fracture toughness is also related to Charpy impact energy of 5mm U notched specimen, 2.5mm saw cut specimen and 2.5mm saw cut specimen with fatigue crack. Characteristics of fracture surface morphology of tensile fracture surface, impact fracture surface and three point bending fracture surface are presented. The features of the stretched zone formation ahead of fatigue crack is presented in relation to the hardness of cold forging dies. Finally the relation between stretched zone width and fracture toughness of structural materials including cold forging die steels is discussed and is expressed quantitatively.

## Experimental Procedure

### Materials

The used materials were commercial cold forging die steels such as tool steels of SKD61,SKD11 and QCM8,high speed steels of YXM1,YXM4,YXR3,YXR33 and YXR7,powdered high speed steel of HAP72 and cemented carbide GM60. The chemical compositions of these steels are shown in Table1. The Rockwell C scale hardness number of these steels after quenching and tempering are shown in Table1.The heat treatment conditions are summarized in Table2.

Table1.Chemical compositions and hardness of tested cold forging die steels

| Steels | Chemical compositions[mass%] | | | | | | | | | | Hardness |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Cr | W | Mo | V | Co | HRC |
| SKD61 | 0.39 | 1.0 | 0.4 | 0.030max | 0.010max | 5.15 | | 1.4 | 0.8 | | 52 |
| SKD11 | 1.5 | 0.25 | 0.45 | 0.025max | 0.010max | 12.00 | | 1.0 | 0.35 | | 61 |
| QCM8 | SKD11 modified steel | | | | | | | | | | 61 |
| YXM1 | 0.85 | 0.25 | 0.35 | 0.025max | 0.010max | 4.10 | 6.5 | 5.3 | 2.05 | | 61 |
| YXM4 | 0.85 | 0.25 | 0.35 | 0.025max | 0.010max | 4.15 | 6.5 | 5.3 | 2.05 | 5.0 | 64 |
| YXR3 | 0.65 mass% carbon matrix high speed steel | | | | | | | | | | 61 |
| YXR33 | 0.54 mass% carbon matrix high speed steel | | | | | | | | | | 59 |
| YXR7 | 0.78 mass% carbon matrix high speed steel | | | | | | | | | | 64 |
| HAP72 | 2.1 | | | | | 4.00 | 9.5 | 8.2 | 5.0 | 9.5 | 67 |
| WC-Co | cemented carbide GM60 | | | | | | | | | | 68 |

Table2. Heat treatment

| Steels | Heat treatment |
|---|---|
| SKD61 | 1073Kx4h,1303Kx1.67h,OQ + 843Kx2.25h,813Kx2.25h,AC |
| SKD11 | 1073Kx4h,1303Kx1.67h,OQ + 773Kx3h,723K3.33h,AC |
| QCM8 | 1073Kx4h,1303k x1.67h,OQ +813Kx2.17h,813Kx 2.17h,AC |
| YXM1 | 1123Kx2.25h,1293Kx0.42h,1413Kx0.42h,OQ + 838Kx1.67h,843Kx2.25h |
| YXM4 | 1123Kx2.25h,1293Kx0.42h,1453Kx0.42h,OQ + 838Kx1.67h,843Kx2.25h |
| YXR3 | 1123Kx2.25h,1293Kx0.42h,1413Kx0.42h,OQ + 813Kx2.17h,813Kx2.17h,813Kx2.08h,AC |
| YXR33 | 1123Kx2.25h,1293Kx0.4h,1413Kx0.42h,OC + 813K x2.17h,813Kx2.17h,813Kx2.17h,AC |
| YXR7 | 1123Kx 2.25h,1293Kx0.42h,1413Kx0.42h,OC + 818Kx2.0h,818Kx2h,818Kx2h,AC |
| HAP72 | 1123Kx2.25h,1293Kx0.42h,1453Kx0.42h,OQ + 838Kx1.67h,843Kx2.25h,873Kx2h,AC |
| WC-Co | |

Note OQ: oil quench, AC: air cool

### Tensile test

The round rod specimens standardized in JIS Z 2241 with 8 mm diameter, 38mm long in parallel section and 180mm long were prepared for tensile test. The tensile tests were conducted by use of a tensile testing machine(55kN).

### Impact test

Specimens with 5mm U notch, 2.5 mm saw cut and 2.5mm saw cut with fatigue crack (1.64-2.25mm) were prepared for impact tests. These specimens were 55mm long, 10 mm wide, and 10mm thick. The impact tests were conducted for these specimens by use of Charpy impact testing machine (310J).

**Fracture toughness test**
The specimens with 55mm long, 10mm wide and 10mm thick were prepared. Fatigue crack with length of 1.64 to 2.25mm was introduced ahead of saw cut notch with 2.5 mm long. Fracture toughness tests were conducted in accordance with ASTM Standard E399-90 by use of Shimadzu servopulser(100kN).

**Fracture surface observation**
Tensile fracture surfaces, impact fracture surfaces with different notch figure and three point bending fracture surfaces were observed by SEM(JSM5500S).

**Results and Discussion**

Fig.1 shows the ultimate tensile strength and elongation of cold forging die steels as a function of Rockwell C scale hardness number. The higher the hardness the higher the ultimate tensile strength is. On the contrary the higher the hardness the smaller the elongation is. Because of the higher hardness of cold forging die steels the elongation is very small. The cup and cone type fracture surface was

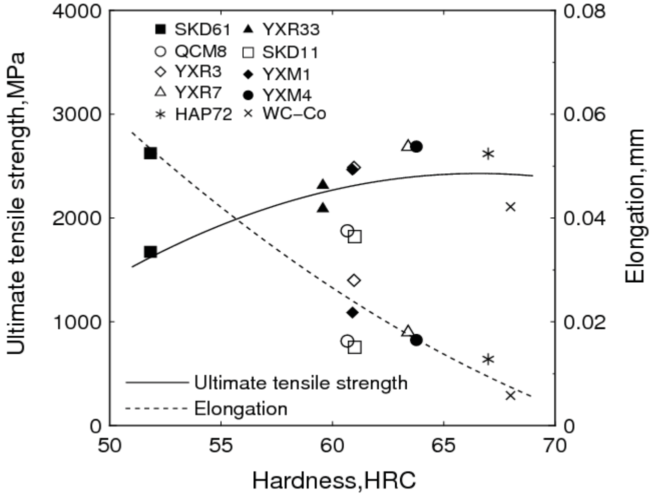


Fig.1 Relation among ultimate tensile strength, elongation and Rockwell C scale hardness number of cold forging die steels.

observed on SKD61 with relatively smaller hardness. The brittle fracture surfaces were observed on the harder steels. Intergranular fracture surfaces were predominant for WC-Co.
Fig.2 shows Charpy impact energy of cold forging die steels with different notch figure. It is obvious that the influence of notch figure on Charpy impact energy is prominent in SKD61. The larger the hardness the smaller the Charpy impact energy is. The Charpy impact energy of cold forging die steels are low as compared with those of other ductile structural steels . It can be concluded that the Charpy impact energy of cold forging die steels is very sensitive to the notch figure. Macroscopic fracture surfaces of 5mm U notched specimens were brittle with radial zone. The shear lips were observed on SKD61 with relatively smaller hardness. Macroscopic fracture surfaces of 2.5mm saw cut and2.5mm saw cut with fatigue crack were more brittle. Shear lips were not observed for all tested specimens except SKD61 steel. Cleavage fracture surfaces were predominantly observed on fracture surfaces of all tested steels except WC-Co. The fracture surface of WC-Co was intergranular. The stretched zone was clearly observed between fatigue fracture surface and unstable fracture surface for all tested steels

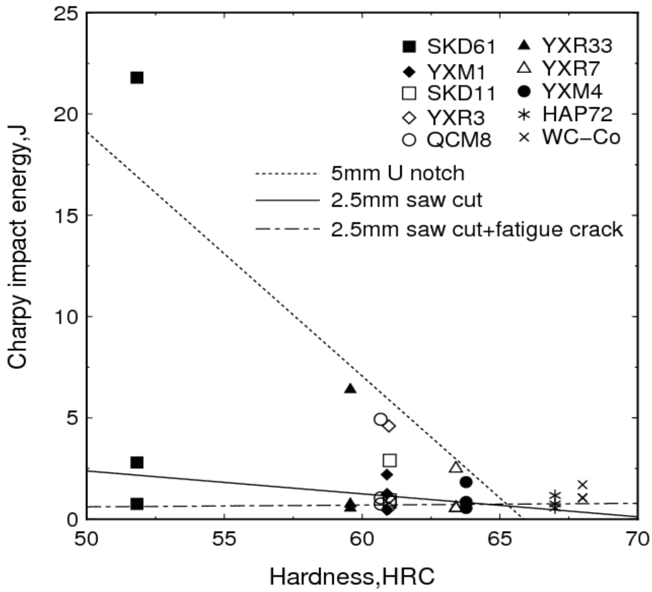


Fig.2 Charpy impact energy of cold forging die steels with different notch figure.

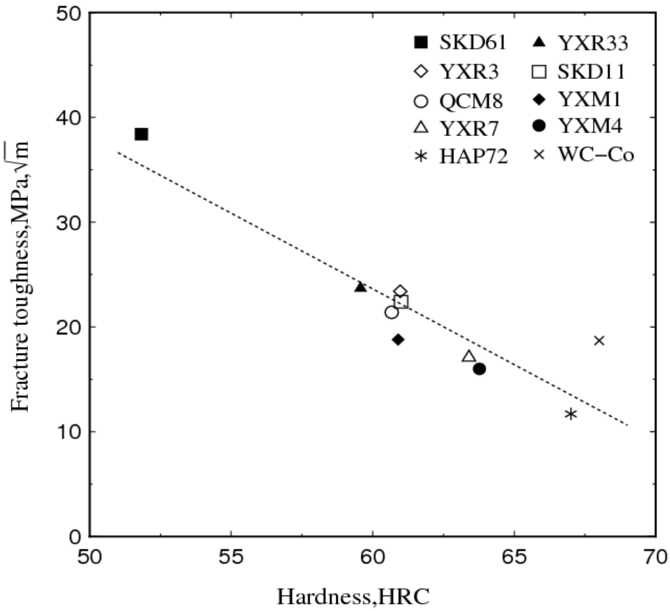


Fig.3 Relation between fracture toughness and hardness of cold forging die steels.

except WC-Co. Fig.3 shows fracture toughness of cold forging die steels as a function of Rockwell C scale hardness number. The fracture toughness is well correlated to hardness and is expressed as follows.

Fracture toughness (MPa)=−1.445 x HRC+110.37

The higher the hardness the smaller the fracture toughness is. Fig.4 shows an example of relation between load and crack opening displacement in the result of fracture toughness test. In this diagram the hatched area can be recognized as a crack initiation energy. Crack initiation energy is well correlated to Rockwell C scale hardness number (Fig.5) and is expressed as follows.

Crack initiation energy(J)=−0.009xHRC+0.595

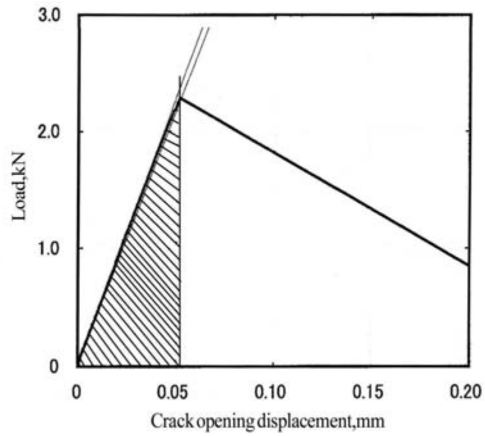


Fig.4 Relation between load and crack opening displacement.

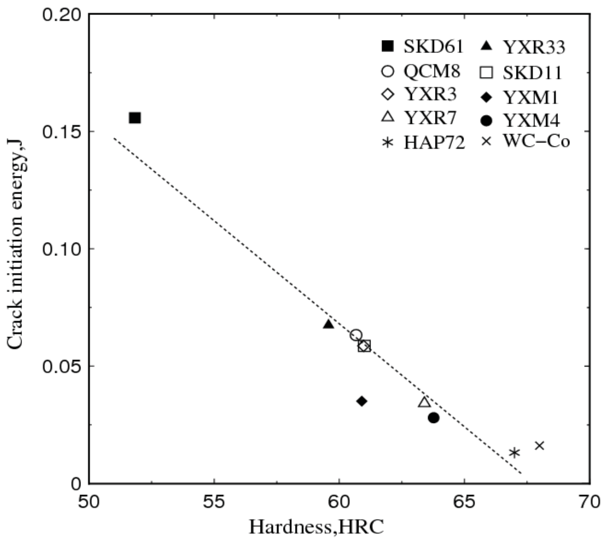


Fig.5 Crack initiation energy as a function of Rockwell C scale hardness number.

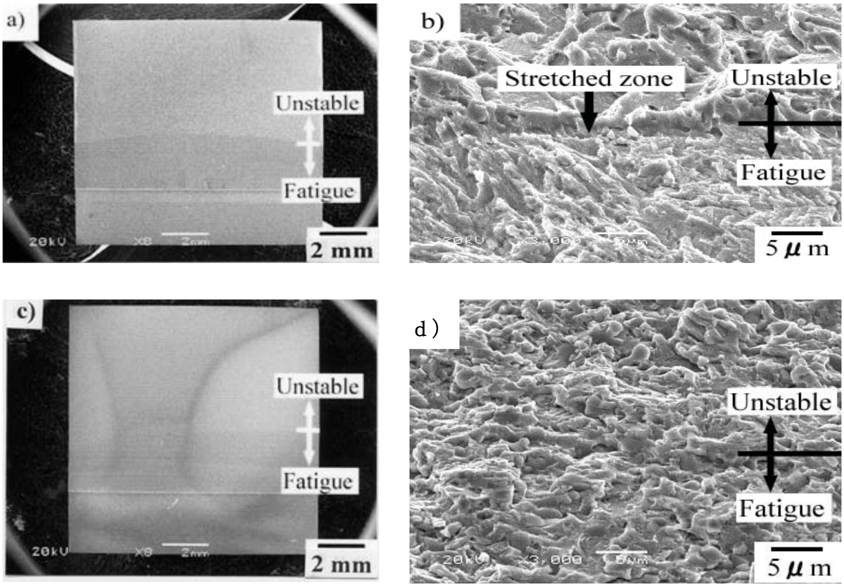


Fig.6 Stretched zone on three point bending fracture surface.
a),b) SKD61
c),d) HAP72

Fracture surface morphologies of three point bending fracture surfaces are similar to Charpy impact fracture surfaces with 2.5mm saw cut with fatigue crack. The stretched zone was clearly observed on fracture surface between fatigue and unstable fracture. Fig.6 shows three point bending fracture surfaces of SKD62 and HAP72. It is easily discriminate between fatigue and unstable fracture surface from macroscopic fracture surfaces [Fig.6a),c)]. The stretched zone can be clearly identify between fatigue and unstable fracture surface[Fig.6b),d)]. The stretched zone width can easily be measured by SEM with low magnification without small error and the stretched zone width was almost constant. The stretched zone width was correlated to fracture toughness. It can be qualitatively mentioned for cold forging die steels that the larger the stretched zone width the smaller the fracture toughness is. Bates and Clark showed that the stretched zone width is well correlated with $Kc/\sigma_y$[4]. One of the authors has confirmed that this relation is applicable for wide range of ductile structural materials [7]. In the results of this research the relation between stretched zone width and $Kc/\sigma_y$ can be depicted for various kinds of structural materials including cold forging die steels as shown in Fig.7. The relation between SZW($\mu$m) and $Kc/\sigma_y$($\sqrt{\ }$mm) can be expressed as shown below.

$$SZW(\mu m)=3.28(Kc/\sigma_y)^{1.24}$$

One of the authors has published that dynamic fracture toughness is well correlated to stretched zone width for hot forging die steels[8]. This relation proved to be useful of quantitative analysis of hot forging die failures. The reason of failures of hot forging dies such as connecting rod, reverse gear and flange york have already been clarified by use of the relation between dynamic fracture toughness and stretched zone width. In the case of cold forging die failure the stretched zone was observed on the fracture surface of a punch as shown in Fig.8. This means that the quantitative analysis can be possible for failure analysis of cold forging dies by measuring stretched zone width.

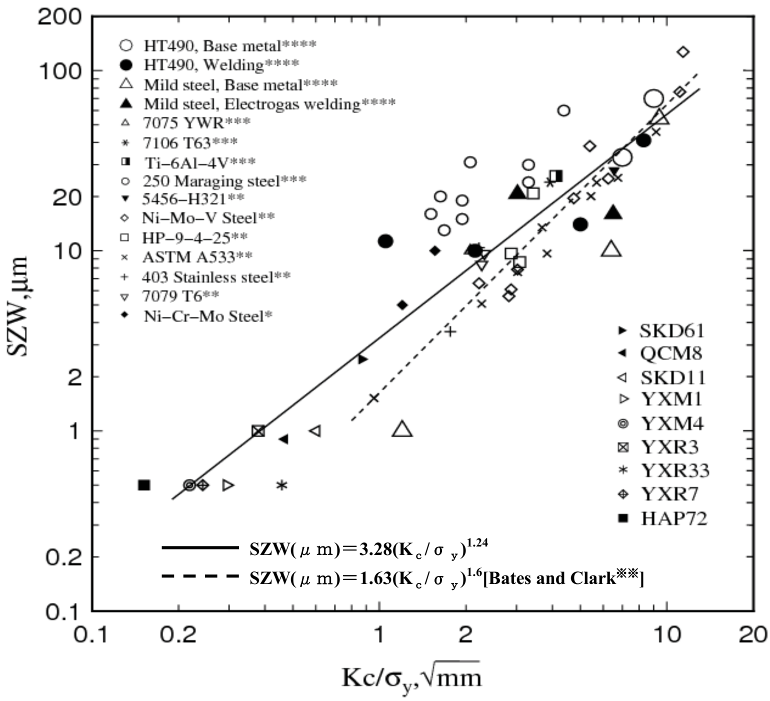


Fig.7 Stretched zone width as a function of Kc/ $\sigma_y$.
※ Spitzig[5], ※※Bates and Clark[4], ※※※Brothers[6]※※※※,Ebara et al.[7]

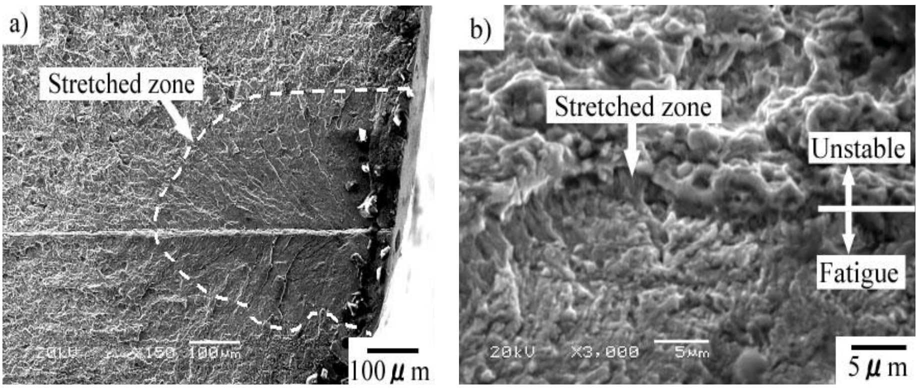


Fig.8 Fracture surface of cold forging die.

## Conclusions

In order to evaluate fracture behavior of cold forging die steels tensile tests, impact tests and three point bending fracture toughness tests were conducted. The main conclusions are as follows.

1. The higher the Rockwell C scale hardness number the higher the ultimate tensile strength is. The higher the Rockwell C scale hardness number the smaller the elongation is.
2. Charpy impact energy of 5mm U notch ,2,5mm saw cut and 2.5mm saw cut with fatigue crack is well correlated to Rockwell C scale hardness number.
3. Fracture toughness and crack initiation energy of the saw cut specimen with fatigue crack is well correlated to Rockwell C scale hardness number.
4. The stretched zone width is well correlated to fracture toughness. The relation between stretched zone width and fracture toughness for structural materials including cold forging die steels can be expressed as $SZW(\mu m)=3.28(Kc/\sigma_y)^{1.24}$.

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