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Simulation of Cold Formability for Cold Forming Processes

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1. Introduction

Massive metal forming processes include several manufacturing methods like drawing, extrusion, forging, coining and rolling. As manufacturing processes, these methods offer good mechanical properties to the products, a short production time, high productivity and optimal material utilization. These advantages are normally achieved with rather large production quantities because of the high cost of tooling and long set-up times of the production lines. However, potential savings in energy and material can be expected when medium and large production quantities are produced. (Kivivuori, 1987 b).

Normally massive metal forming processes are carried out using cold, warm or hot working conditions. The forgeability of deformed material or the limitations due to the deformation process used are the limiting factors when these massive metal forming processes are used.

The cold forgeability of a material can be measured by using upsetting, tensile or torsion tests. The upsetting test based either the measuring of critical reduction in height or the critical strain values measured from the free surface of the upset specimen are the methods most used for predicting the formability of the material during a massive cold forming process.

2. Forgeability of materials

Formability (Workability, Forgeability) is the ability of a material to deform plastically without the occurrence of any defect in a forming process (Dodd, 1996). A defect occurs when the properties of a component do not conform to the design specifications, making it unsuitable for the purpose for which it was designed. The occurrence of the defect depends on the geometry of the tooling, forming conditions and the properties of the work piece material. (ICFG document 11/01, 2001)

2.1 Ductility of materials

Cold forming is limited either by the high deformation force or the ductile fracture. It has been generally accepted that ductile fracture results when voids are formed around inclusions and other heterogeneities from the early stage of forming. If the deformation is continued, the voids grow and coalescence into a microcrack which further grows and becomes visible when it reaches the specimen surface (Kivivuori, 1978).

The stress and strain relations as well as alloying, microstructure and strain history also have a great influence on the ductile fracturing. Very important factor affecting the cold forgeability is the inclusion properties of the steel. The inclusion properties include the size, shape and volume fraction of inclusion and their distribution as well as chemical composition.
Alloying of steel normally reduces the ductility. Lamellar carbides as in pearlite, increase flow stress and strain hardening thus reducing ductility more than spheroidical carbides.
For practical purposes the effects of metallurgical variables or forgeability and machinability are roughly summarized in Table 1 (ICFG document 11/01, 2001).

METALLURGICAL PARAMETER		COLD FORGEABILITY				TOOL WEAR IN MACHINING	
		FLOW STRESS		DUCTILITY			
		Yield stress	Rate of strain hardening	Fracture strain in RD	Critical height reduction	HSS tool	Carbide tool
Chemical composition	C	↑↑	↑	↓	↓↓	↑↑	↑↑
	Si	↑↑	↑↑	↓	↓↓	↑	↑
	Mn	↑	↑	↓	↓	↑	↑
	P	↑	↑	↓	↓	→	→
	S	↓	↓	→	↓↓	↓↓	↓
	Cr	↓	↑	↑	↑	→	→
	Ni	↑	↑	↓	↓	↑	↑
	Mo	↑	↑	↓	↓	↑	↑
	Al	→	→	→	→	→	↑↑
	V	↑	U	↓	↓	↑	↑
	Nb	↑	U	↓	↓	↑	↑
	Ti	↑	U	↓	↓	↑	↑↑
	N	↑↑	↑↑	↓	↓	↑	↑
	B	→	→	→	→	→	→
	Metallic residuals	↑	↑	↓	↓	→	→
	Ca	→	→	→	→	↓	↓↓
Microstructure	Small grain size	↑	↑	→	→	↑	↑
	Lamellar carbides	↑	↑	↓	↓	↓	↓
	Segregations	→	→	↓	↓	↑	↑

↑ Increase ↓ Decrease → Not effective
↑↑ Strong increase ↓↓ Strong decrease U Unknown

Table 1. The effect of chemical composition and microstructure on cold forgeability and tool wear in machining (ICFG document 11/01, 2001).

2.2 Defects in cold forging

When considering formability the type of the defect must be specified. The same material may show good formability, eg. with respect to ductile fracture, or very poor formability with respect to galling (ICFG document 11/01, 2001). The influence of the material properties on the different types of defects can be seen in Fig. 1.

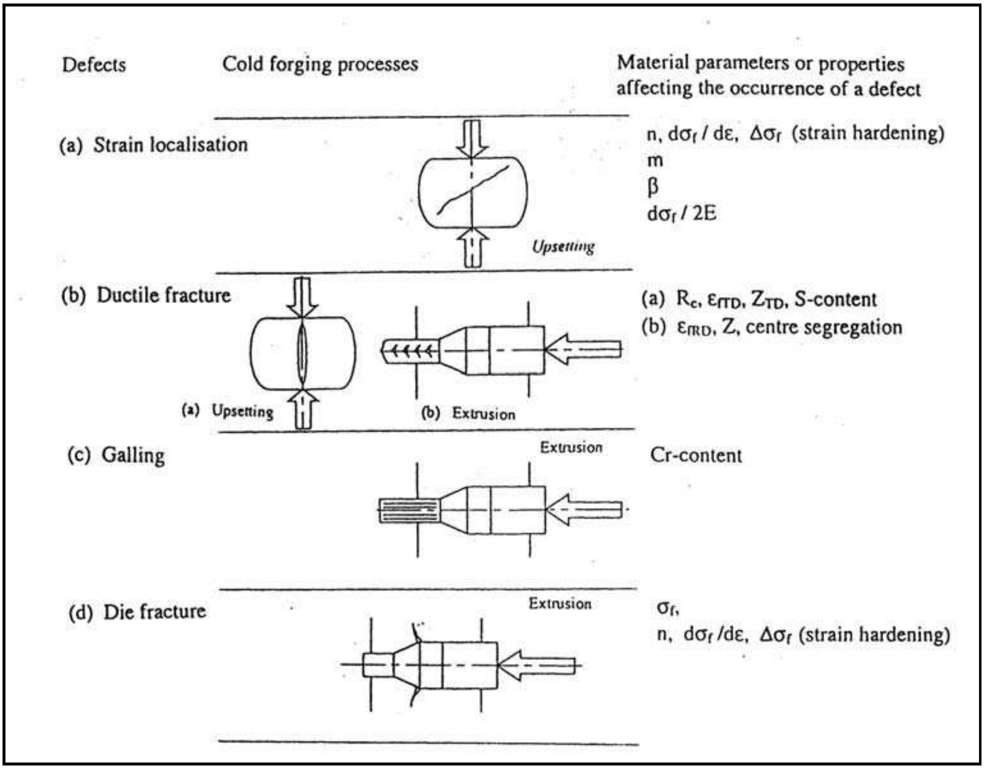

Fig. 1. Examples of defects in massive forming processes and their relation to material parameters (ICFG document 11/01, 2001).

3. Cold forgeability testing

Because of the complex nature of cold forgeability, there are no single test that can be used to evaluate it (ICFG document 11/01, 2001). Several testing methods to measure material forgeability have been developed.
Compression tests are normally used to measure material forgeability in massive metal forming processes (Kudo, 1967). On the other hand, for assessing the material formability upsetting tests based on measuring the critical reduction or forming limit diagram are often used. Therefore, for cold forgeability testing, firstly, compression tests for flow stress and upsetting tests for ductility and forming limit testing are recommended (ICFG document 11/01, 2001).

3.1 Compression testing

Flow stress testing is normally carried out by using compression tests under uniaxial stress state. To achieve this condition and to reduce the frictional forces between tool and specimen either conical compression tests or Rastegaev compression tests must be used. In fig. 2 the test specimens normally used for uniaxial compression testing has been shown.

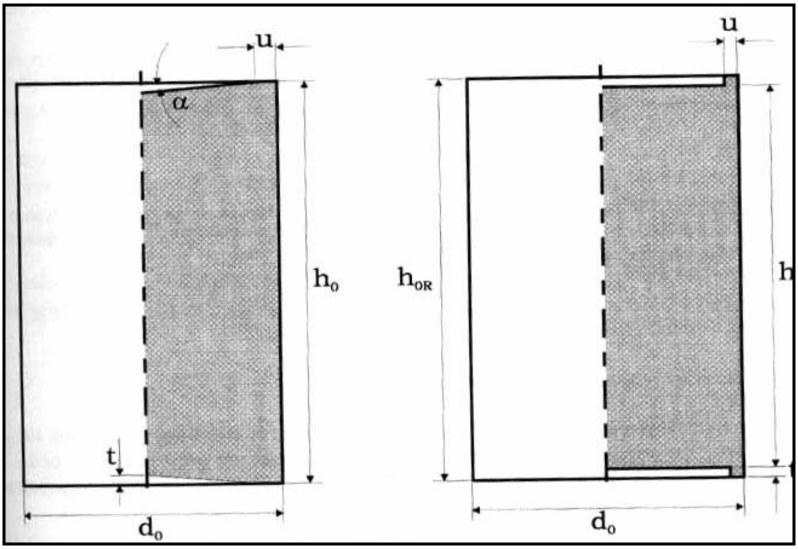

Fig. 2. Test specimens of compression test (ICFG document 11/01, 2001).
Left: Conical compression test
Right: Rastegaev compression test.

The dependence of the flow stress (σ) on strain (ε), strain rate ($\dot{\varepsilon}$) and temperature (T) can be expressed by

$$\sigma = \sigma\,(\varepsilon, \dot{\varepsilon}, T). \tag{1}$$

This equation cannot be expressed generally, but rather for a particular material and a limited strain, strain rate and temperature range. The most widely used equation for steel and aluminum is the Hollomon type, which for isothermal conditions can be written in the form

$$\sigma_{iso} = K\,(\varepsilon/\varepsilon_o)^n\,(\dot{\varepsilon}/\dot{\varepsilon}_o)^m \tag{2}$$

where ε_o, $\dot{\varepsilon}_o$, K, n and m are material constants. Assuming that $\varepsilon_o = 1$ and $\dot{\varepsilon}_o = 1\ s^{-1}$ eqn. (2) takes the form

$$\sigma_{iso} = K\,\varepsilon^n\,\dot{\varepsilon}^m \tag{3}$$

The constants are determined from experimental stress-strain data. The strain-hardening exponent, n, is a measure of the ability of the material to harden as a result of deformation. the strain-rate hardening exponent, m, gives the response of a material to the strain rate. At ambient temperatures the strain-rate hardening is negligible since the m value for most metals is small.

In rapid forming, the temperature of the material being deformed can increase owing to deformation heating. The temperature dependence of the flow stress can be expressed by

$$\sigma = \sigma_{iso}\,(1 + \beta\,\Delta T) \tag{4}$$

where β is an experimentally determined constant and ΔT is the temperature difference from the isothermal condition.

3.2 Upset testing

When measuring ductility of the material upsetting test based on measuring of the critical reduction can be used. A collective round-robin study of a standardized cold upsettability test with a cylindrical test specimen compressed between grooved dies (fig. 3) was carried out by CIRP (Kudo, 1975).

To prevent effect of surface defects the test specimens must be machined out from the bars with sharp edged tool. Specimens are incrementally upset with the reduction increase of 2.5% until fracturing. The fracture of the specimen has detected after each increment and upsetting has continued until the fracture has observed by naked eyes.

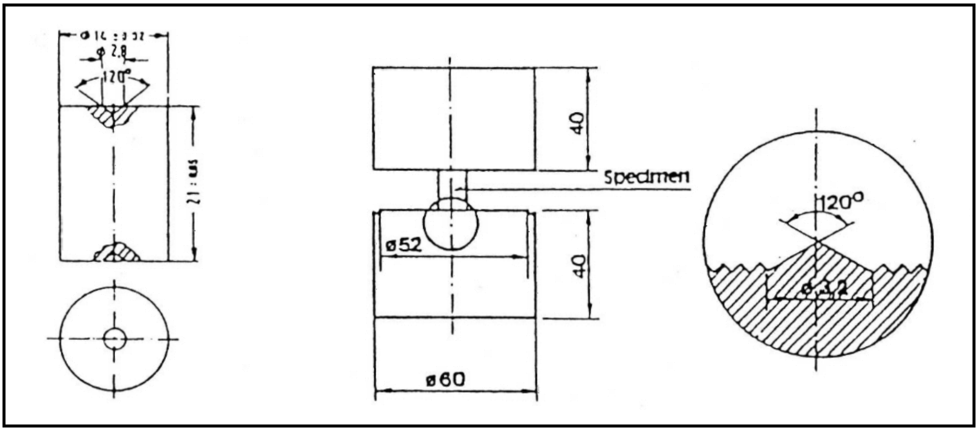

Fig. 3. Test specimens and grooved dies used in standardized upsetting testing (Kudo, 1975).

Collecting all fracture data of the testing serie containing normally 20 test pieces the critical reduction value can be calculated. The critical reduction value is obtained when 50 % of all fractures observed during testing have reached. The critical reduction values of several test materials can be seen in fig. 4.

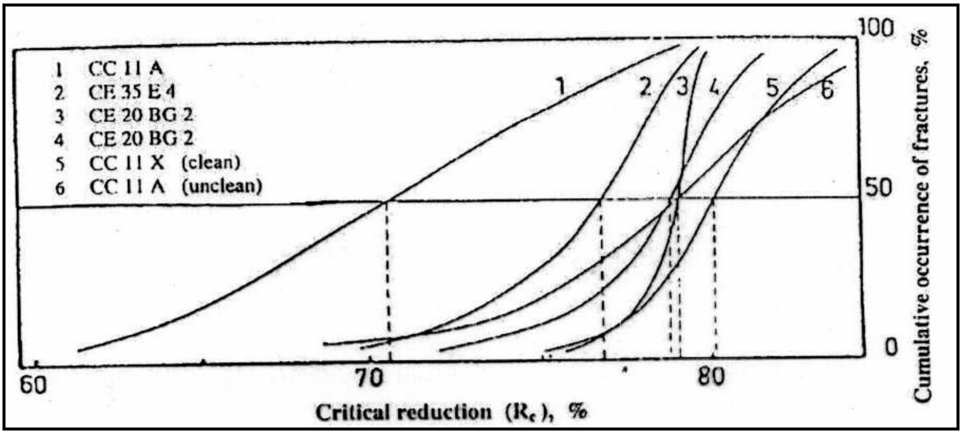

Fig. 4. The critical reduction of several materials tested in upsetting testing (ICFG document 11/01, 2001).

The pre-drawing has a considerable effect on the values of the critical reduction. The increased values of critical reduction have a maximum point at the pre-drawing reduction about 30 %, as can be seen in fig. 5. However, if the specimens are pulled in the tension testing machine without drawing tool, no increasing tendency have been noticed, but the value of critical reduction decreased according to fig. 5. It is significant that the specimen tensioned to the point of plastic instability could still be upset 75 % without cracking (Kivivuori, 1987 a)).

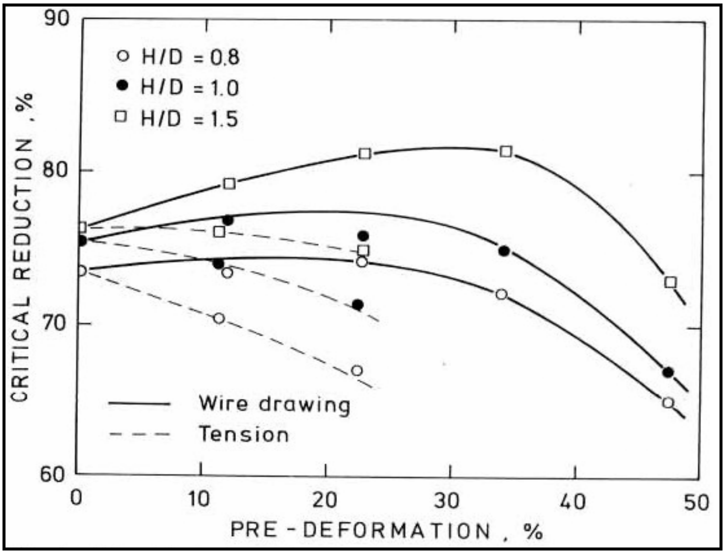

Fig. 5. The effect of pre-drawing on the critical reduction when specimens with H/D ratios of 0.8, 1.0 and 1.5 are upset in sticking friction conditions (Kivivuori, 1987 a)).

3.3 Formability testing

For the determination of the formability diagrams, a grid of 2 mm diameter circles was electrochemically etched on the surface of the specimens. Coordinate axes corresponding to the cylindrical symmetry used in the determination of fracture strains of the specimens, are presented in fig. 6.

When the cylindrical specimen is compressed the external surface barrels, fig. 6, developing tensile stresses at the free surface. In the case of severe barreling even the axial surface stress may become tensile which favors fracturing (Kivivuori, 1978). The surface strain values can be calculated using the following equations

$$\varepsilon_z = \ln (h/h_o) \quad (5)$$

$$\varepsilon_\theta = \ln (w/w_o) \quad (6)$$

$$\varepsilon_r = -(\varepsilon_z + \varepsilon_\theta) \quad (7)$$

where h_o and w_o are the original and h and w the current dimensions of grid marks on the surface of the specimens (see fig. 6).

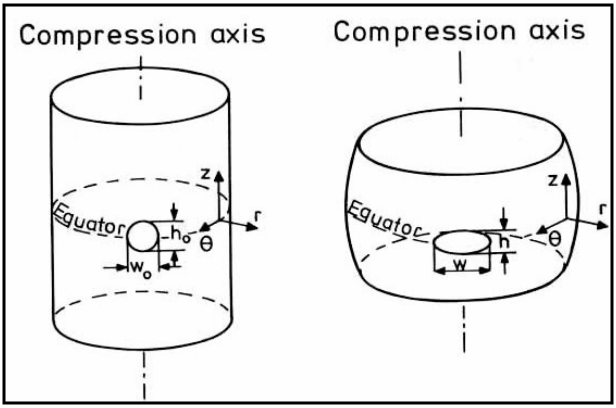

Fig. 6. Coordinate axis of the cylindrical symmetry on the surface of original and upset specimen (Kivivuori, 1987 a)).

Specimens will be compressed incrementally and the surface strain values will be measured after each compression step. Compression steps will be added incrementally until the specimen fractures. The strain values at fracturing are measured and plotted on the ε_z - ε_θ coordination axis. Formability limits can be presented as a forming limit diagram (FLD) consisting of straight line having slopes between -0.33 and -0.7 (fig. 7). In the case of steel CC 35, the FLD consists of two lines as seen in fig. 7. One of these has roughly the direction of homogeneous deformation while the other is placed at higher strain values and limits the total strain in the circumferential direction.

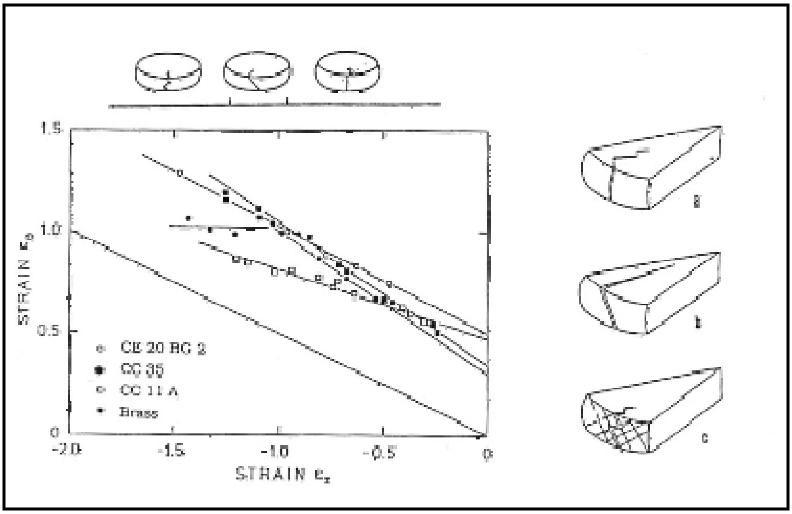

Fig. 7. Formability diagrams for several materials. Cracking modes and their occurrence in the forming limit diagrams (ICFG document 11/01, 2001).
a) longitudinal cracking at low strain values
b) oblique cracking at medium strains
c) shear cracking at large strain values.

To examine the validity of the formability limit diagram, two series of bolt heading tests were carried out using H/D ratios of 1.7 and 1.8. The results of these industrial bolt heading tests are given in fig. 8. It can be seen that the strain values in the heading process are quite far from the critical values measured with compression testing. This result agree well with the practical observations.

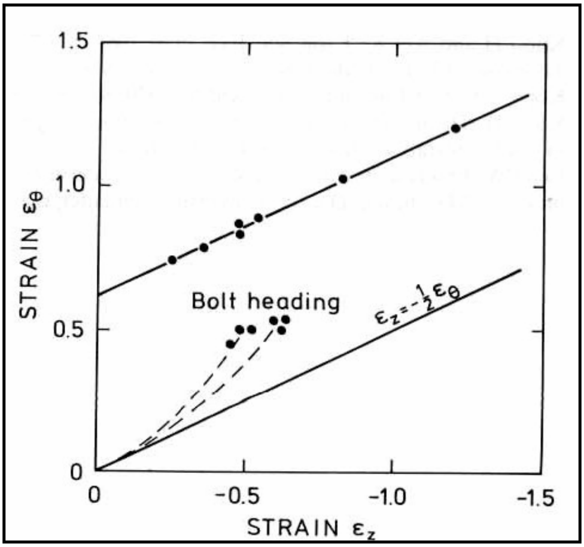

Fig. 8. Strain values in the cold heading of a bolt compared to the forming limit diagram of the material (Kivivuori, 1987 a)).

3.4 Other testing methods

The uniaxial tensile test is probably the most common used mechanical material testing method giving information on the flow stress level and ductility. However, there are serious limitations when using tensile testing to examine cold forgeability parameters.

To evaluate ductility, the reduction of area in the tensile test, Z, or fracture strain, ε_f, may be used. The fracture strain measured with tensile test specimens taken in rolling direction, ε_{RD}, can be utilized to asses forgeability in such cold forming methods, as bending, expanding, drawing and forward extrusion (ICFG document 11/01, 2001). On the other hand, in upsetting operations ε_{RD} is not relevant but fracture strain measured in the transverse direction, ε_{TD}, can be employed to predict the critical reduction as seen in fig. 9.

The torsion testing is sometimes used to assess forgeability. To avoid the variation of shear stress across the wall thickness thin walled tubes may be used to obtain stress-strain curves to high strain and strain rates. Torsion test has the advantage of allowing very large strains to be generated (ICFG document 11/01, 2001).

Plane strain compression test is used to estimate accurately flow stress at very large strains and high strain rates. The barreling occurring in normal compression testing at high values of friction is avoided using plane-strain compression. The test specimen is in the form of thin strip which is compressed across its width by narrow plates.

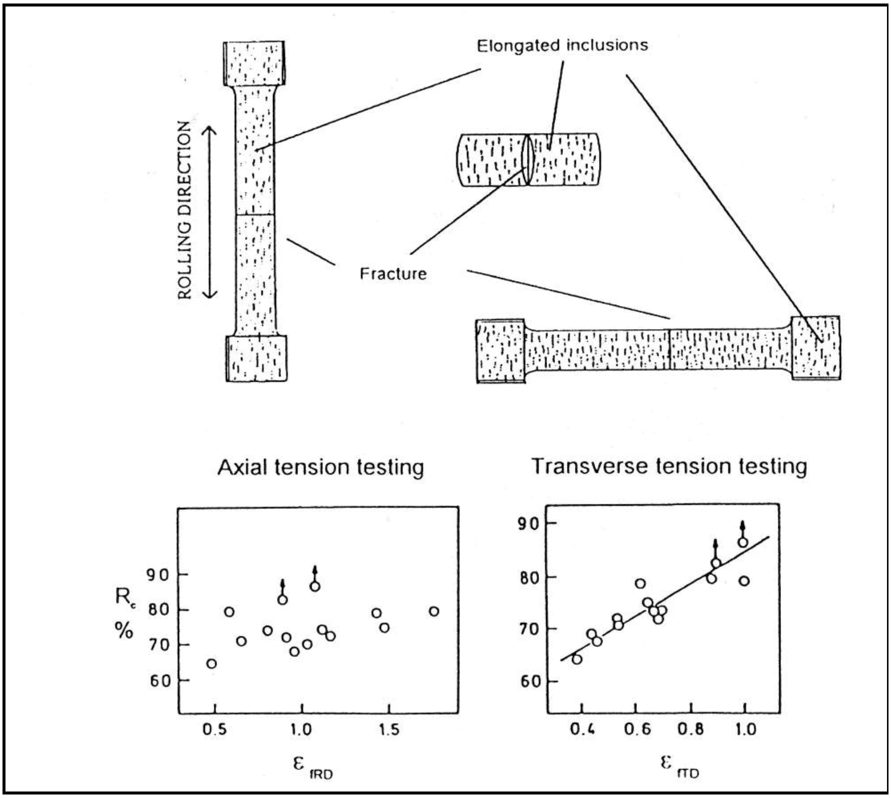

Fig. 9. The critical height reduction in cold upsetting against axial and transverse fracture strains, ε_{RD} and ε_{TD}, respectively, measured in a uniaxial tensile testing (ICFG document 11/01, 2001).

4. Conclusions

The cold forgeability of the materials can be measured using several testing methods. Flow stress testing is normally carried out by using tensile or compression tests under uniaxial stress state. Other testing methods used are torsion and plane strain testing methods.

The formability of materials was determined by testing small cylindrical specimens under uniaxial compression. Using upsetting testing the critical reduction values of the materials can be measured. The forming limit diagrams can be measured by using compression testing at different frictional and geometrical conditions.

The effect of wire drawing on the cold forgeability was studied by using the upsetting test. The pre-drawing has a considerable effect on the values of the critical reduction. The increased values of critical reduction have a maximum point at the pre-drawing reduction about 30 %.

The critical reductions have been measured and compared with the values of reduction of area measured using uniaxial tensile testing. It was found that the reduction in area measured by tensile testing does not describe the cold upsettability of a material if the axial tensile testing was used. Therefore, the transverse tension testing must be employed to predict the value of critical reduction of the material.

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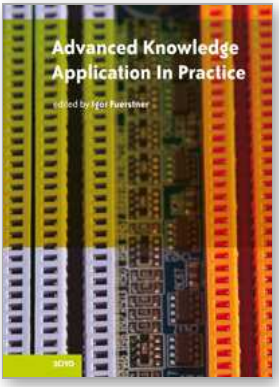
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