STRENGTH AND TOUGHNESS PROPERTIES OF STEELS UNDER DYNAMIC LOADING

Jian Fang
BAOSTEEL Research Institute
Technical Center, Baoshan Iron & Steel Co., Ltd.,
Shanghai 201900, China

ABSTRACT

The specific type of specimens were prepared from X80 pipeline steel with perpendicular sampling orientation for the dynamic testing of impact tensile at given strain rate, 10^2 /s and instrumented pendulum impact with the given stress intensity factor rate, 5×10^5 MPa·m$^{1/2}$/s in the present paper. The comparison of the yield stress and tensile strength corresponding to quasi static and dynamic loading clearly indicates that the strength of X80 steel is sensitively dependent of the strain rate change. With the increase of strain rate from 10^{-2}/s to 10^2/s, the strength values rise by nearly 100MPa. The flow yield stress i.e. σ_{yd} was accurately determined as the average of the first two peak and valley stress values on stress-strain curve from impact tensile. The correlation of σ_{yd} and F_{gy} obtained from instrumented impact by means of Server equation was proved to be satisfactory. Whereas, The application of Server equation for the estimation of dynamic ultimate tensile strength i.e. σ_{bd} from maximum force i.e. F_m was invalid just for the studied steel here. In addition, dynamic crack extension resistance curve, J-Δa, was acquired for the evaluation of toughness property, also effectively revealing the mechanism of crack initiation and growth under dynamic loading.

Introduction

As regards the increasing demand on the experimental characterization of the dynamic properties of HSLA steel and the performance on real service conditions, relative to the strain rate of 10^1-10^3 s^{-1}, so many uniaxial loading solutions have been proposed to obtain the stress-strain relation by hydraulic servo system or the Split Hopkinson Pressure Bar in the decades. Unfortunately, the complexity of the hardware constitution and high cost of testing operation incur the restriction of its prevalence in industrial laboratory in comparison with Charpy impact.

On the other hand, equipped with load sensor, for instance, the instrumentation tup to record the dynamic loading against time during impact loading period, the conventional Charpy testing has been already developed to be another attractive solution for performing dynamic testing [1], combined with the subsequent Elastic Plastic Fracture Mechanics analysis on the instrumentation output and so many kinds of hardware accessories, especially the impact tensile device. In the paper, on the basis of instrumented Charpy impact and instrumented impact tensile testing were simultaneously carried out to investigate the dynamic properties of X80 pipeline steel of practice.

Principles

As one of most economic solution performing dynamic testing for metals, pendulum Charpy impact tester with 300J or 450J capacity may provide the loading rate in terms of stress intensity up to 10^5-10^6MPa·m$^{1/2}$/s, described as follows.

$$\dot{K} = \frac{pv}{\sqrt{B}} \tag{1}$$

Here, p is constant, 9016MPa, v is the maximum horizontal velocity which tup reaches as 5.23m/s for the present study, B is the thickness.

Figure 1 shows a typical curve of impact force vs. displacement, with a series of characteristic force points comprising F_{gy}, F_m, F_u, F_a, specified in coincidence with ISO 14556:2000 standard. As a threshold of the extensive dynamic evaluation on the

HSLA and other metal materials, Key Curve and so-called Single Specimen Technique on the basis of EPFM principle were performed dealing with the acquired characteristic force points.

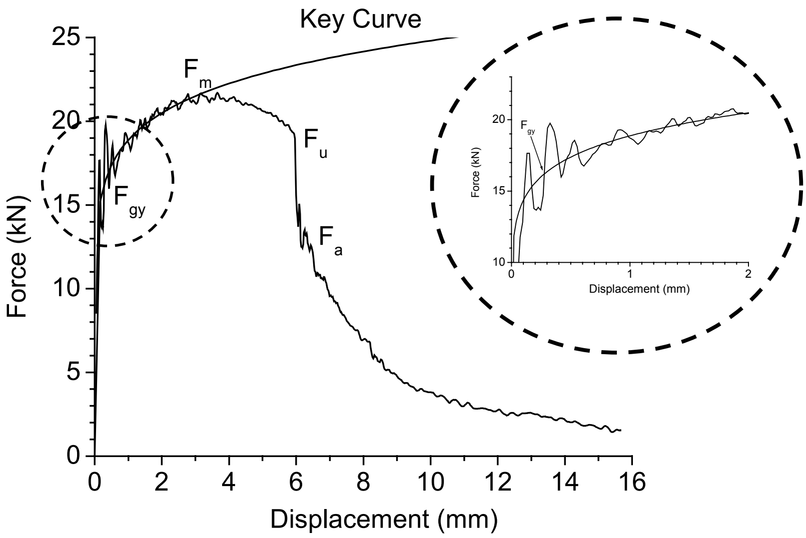

Figure 1. Force-displacement curve by instrumentation method with fitted Key Curve and the location assistant of general yield point as the intersection of KC curve and the rising part of the second oscillation peak.

Different to the uniaxial loading technique such as hydraulic high speed tensile to determine the flow yield stress and ultimate tensile strength, the metallic axial properties and its response to the dynamic conditions could rarely assessed by directly using the F_{gy} and F_m attained by Charpy, due to the intrinsic bending mechanism. Fortunately, the relationship between σ_{yd} and F_{gy} can be constructed by fulfilling Server equation as below [2]. In the study, we also attempt to testify the validation of Server equation when estimating the tensile strength, σ_{bd} from maximum force, F_m.

$$\sigma_{yd} = 2.99 F_{gy} \frac{S}{4B(W-a_0)^2} \tag{2}$$

Due to the crack growth, Key Curve method and modified Rice integration equation [3] are employed to compose the J-Δa curve, describing the stable crack extension behavior during the range from F_m to F_u.

$$J_d = \frac{\lambda}{Bb}\int_0^{\Delta_{pl}} p d\Delta_{pl} \tag{3}$$

$$\Delta a = W - ((\frac{PW^{n+1}}{k\Delta_{pl}^{n}})^{1/2} + a_0) \tag{4}$$

Here in Equation (4), n and k are the coefficients obtained by curve fitting the relationship of impact force and displacement relative to the plastic deformation period from F_{gy} to F_m by means of KC formula, as Equation (5).

$$\frac{PW}{b_0^2} = k(\frac{\Delta_{pl}}{W})^n \tag{5}$$

Experimental

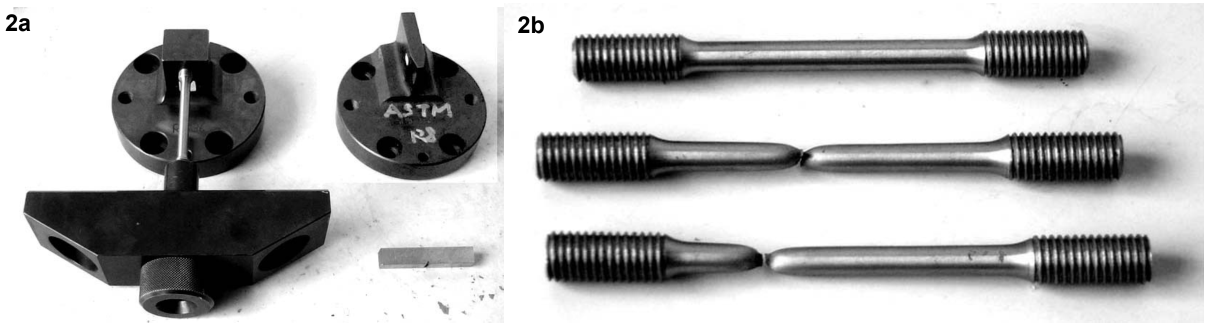

Figure 2. Illustration of the impact equipment and specimens. In Left (2a), instrumented hammer for Impact Tensile and Charpy impact, In Right (2b), miniature thread round bar specimen used in dynamic tensile.

Two batches of standard V notch Charpy specimen with perpendicular orientation (L-T and T-L) according to the rolling direction were prepare from the X80 thick plate, in the meanwhile, thread round bar tensile specimen were also machined with relative sampling orientation (Transverse, T and Longitude, L), see Figure 2b. In the present work, Zwick/Roell RKP 450 is employed to perform the dynamic testing including instrumented impact testing and impact tensile testing, by means of mounting special instrumentation tup and accessories, as illustrated in the Figure 2a. Before being raised to an initial angel, the thread round bar specimen are screwed and fixed between the tup and the tailor block. During the impact, the tup with the specimen transits through the anvil's central gap, while the tailor block is impeded by the stiff anvil's end wall, which leads to the impact loading transferred onto the tensile specimen and the induced breaking.

Results and Discussions
Instrumented impact tensile

The nominal stress-strain curve of miniature round bar specimen under dynamic and quasi static loading were recorded as Figure3, in which the tensile deformation of Longitude batch specimens are plotted as solid line, while dashed lines for Transverse batch.

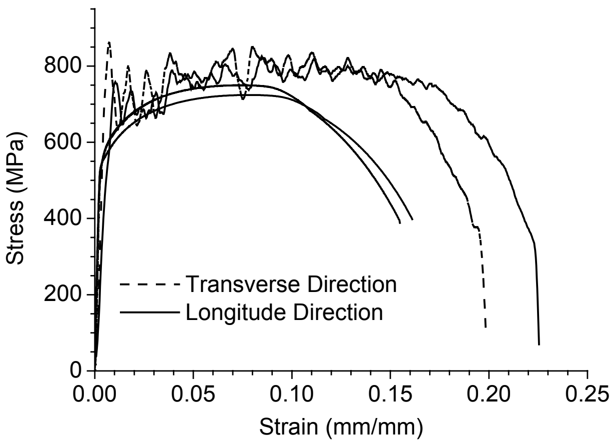

Figure 3. Stress-strain curves obtained by tensile testing under dynamic and quasi static loading conditions.

The oscillation of the signal is induced by the inertia effect between the tail block and stiff anvil, which is magnified by the transmission and reflection of the load wave within the specimen parallel part. Commonly, the strain channel of the static tensile is sampled by using electronic extensometer, which simultaneously measures the increase of the initial gage (in the present study, the parallel length is 50mm), whereas for impact tensile, without any physical sensor such as strain gage or Laser Doplor non-contact extensometer to determine the genuine elongation of gage length, the nominal strain channel is calculated as the ratio of loading point displacement to the initial parallel part, with the assumption that the majority of specimen deformation is contributed by the extension of parallel section. So that, in the Figure 3, It need to be taken into account the strength response of the material under various loading conditions, rather than the superficial comparison of the strain value with different metrological process.

From the Figure 3, the studied material is typically sensitive to the strain rate. With the strain rate increased by 4 orders of magnitude, just from 30 mm/min, i.e. 10^{-2} /s to 5.23 m/s, i.e. 10^{2} /s, the yield strength and tensile strength rise by 100MPa. While the promotion of the yield strength is higher than that of tensile strength, resulting in the reduction of the strain hardening properties of the material used here. It need to be concerned that the anisotropy of the strength property of X80 seems to be relieved by dynamic loading more or less, that is to say, the difference of the strength values between Transverse and Longitude batches of specimens is lower down with the loading condition changed from static to dynamic. Numerical filter technique such as moving smooth method is sometimes proposed to smooth down the oscillation of wave curve affected by the noise signals. Nevertheless considering the capture of the yield stress on the impact tensile curve coupled with the inertia effect, the phase or the strain position of the yielding point will be either shifted earlier or retarding inevitably by exerting numerical filter method. Instead flow yield stress was determined as the mathematical average level of the first TWO pairs of peak and valley values on the curves of nominal stress against strain, so as to remove the fluctuation of the original signals, as listed in the Table 1.

Table 1. Summary of the strength properties evaluated by means of various dynamic loading modes.

impact tensile testing			Charpy impact testing					
No.	σ_{yd} MPa	σ_{bd} MPa	No.	E_t J	F_{gy} kN	F_m kN	σ_{yd} MPa	σ_{bd} MPa
L	703.1	790.0	L-T	333	15.11	21.82	705.8	1019.2
T	734.8	820.1	T-L	300	15.84	21.90	739.5	1023.2

Instrumented Charpy impact testing

The force-displacement curve of instrumented impact testing for the T-L and L-T batches specimens are shown in the Figure 4. Since the impact fracture of X80 at room temperature occurs at the upper shelf of Ductile-Brittle-Transition, the characteristic force points only consist of F_{gy} and F_m, corresponding to the overall shear fracture surface. The Charpy impact force and absorbed energy values were listed in the table, in comparison with those uniaxial tensile properties results from impact tensile testing. Shown in the Figure 4, the E_t of batch T-L specimens are 10% lower than those of L-T, while the general yield force of T-L is little higher than L-T. In addition, in spite of the perpendicular orientation, T-L and L-T specimens act as the identical crack initiation and early crack propagation behavior. The difference of E_t for two batch specimens is dependent on crack resistance properties only when the formed crack grows to a given extent.

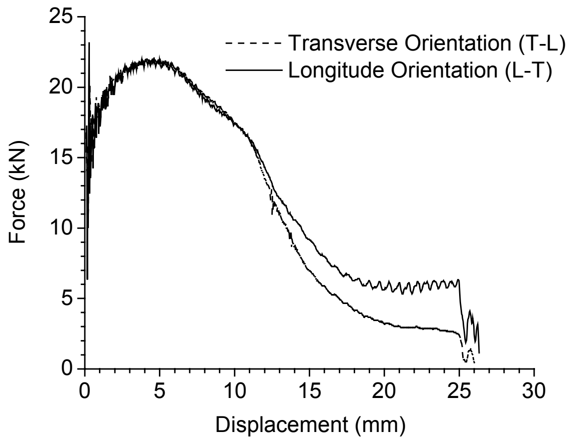

Figure 4. Impact curves of force vs. displacement from instrumented impact testing.

Mentioned as above, material uniaxial flow yield stress could be approximately estimated by means of Server Equation, i.e. Equation (2) based on the instrumented Charpy impact testing. As a result of combinative dynamic testing comprising the impact tensile and Charpy impact, It is possible to validate the correlation between real measured yield stress and the counterpart yield force from Charpy testing, as listed in Table 1 and graphically shown in Figure 5 with histogram. From the

Figure, it is ascertained that, with Server equation, the estimation of σ_{yd} from F_{gy} is of course satisfactory, considering the duplication of higher yield stress of T batch specimen by Charpy testing is so accurately. However calculated dynamic tensile stress σ_{bd} by the same solution from F_m deviates significantly from the measured values.

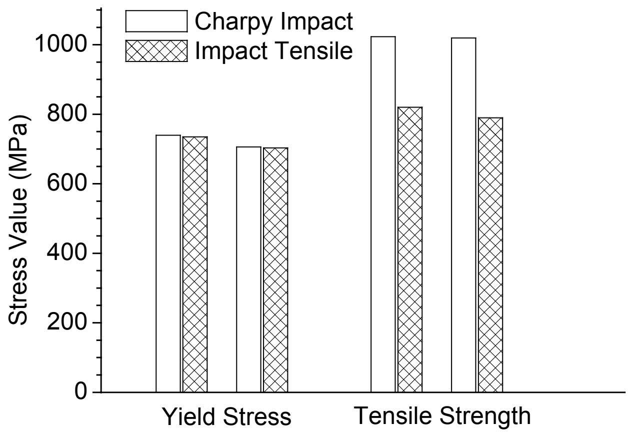

Figure 5. Determined strength properties in comparison with that estimated from Charpy test.

According to ASTM E399, E813, etc., parameters like $\varepsilon(J_{1C}/\sigma_y)$, $\beta(K_{1C}/\sigma_y)^2$ are defined as the critical geometry size or critical crack length, relative to the validation criteria of fracture toughness under in-plane strain condition, which is also helpful for assessing the effect of service conditions, including temperature and loading rate, on the material fracture characters. The smaller the parameters reach, the more probably cleavage fracture may occur. As regards the dynamic loading, J_{1d} and K_{1d} could be determined by using instrumented Charpy impact with fatigue pre-cracking CVN specimen, however it is of more cost and complicated to establish the experimental set-up with temperature controlling to determine the flow yield stress σ_{yd} at specific temperature. The validation of estimating σ_{yd} from F_{gy} exploits an efficient way to obtain fracture toughness and relative yield strength properties at given temperature by unique Charpy testing.

Concerning toughness properties, dynamic crack extension resistance curve, J-Δa, was plotted as Figure 6 by using so-called Single Specimen Analysis Technique [3], i.e. Equation (3) and Equation (4), which has been integrated into the BAOSTEEL exclusive software ImpactPlus 2.0. As above, T-L and L-T has the close crack initiation and propagation toughness until to the 1.5mm crack length accumulated. The slope of J-Δa curve for L-T batch goes upside apart from T-L, corresponding to the higher impact energy consumed for the growth of existing crack. In a word, the distribution of impact energy has been subdivided into components by instrumentation force-displacement curve, with the qualitative analysis of crack formation and propagation by constructing J-Δa resistance curve, which facilitates the total insight into the fracture behavior and underlying mechanism.

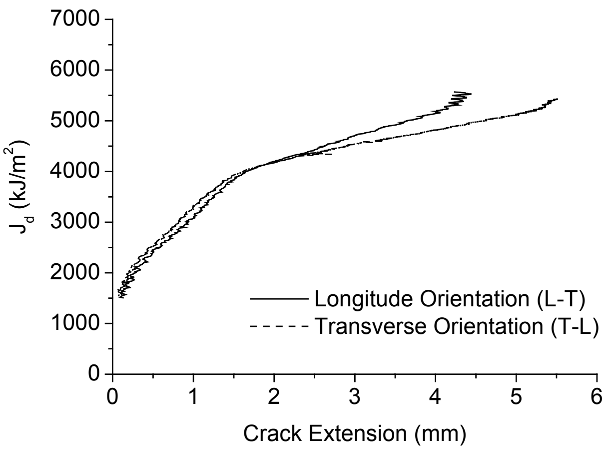

Figure 6. Dynamic crack extension resistance curve from instrumented Charpy impact.

Conclusions

It is feasible and convenient to prepare miniature round bar and Charpy V notch specimens simultaneously from structural steels for conventional tensile, Charpy impact and impact tensile testing, which provides the relative testing rate high up to 10^2 s^{-1} for uniaxial loading and 5×10^5 $MPa\cdot m^{1/2}/s$ for impact in this study, achieving the possibility of acquiring the dynamic response properties of HSLA combined with its quasi static performance all together. As a result, the strength property of X80 pipeline steel is proved to be dependent of the loading rate. The four order of magnitude does rate increase by, Its yield stress and tensile strength rise by 100 MPa. As to remove the noise signals due to the vibration and inertia effect on the impact tensile stress-strain curves, dynamic flow yield stress is nominally calculated as the average of first two peak and valley stress values on the curve.

The validation of the Server equation for the estimation of dynamic yield stress by means of general yield force, i.e. F_{gy} by instrumented impact was also studied by performing correlated testing between impact tensile and Charpy impact. The linear relationship of σ_{yd} with F_{gy} is authenticated satisfactorily, whereas the coincidence of dynamic tensile strength, i.e. σ_{bd} with F_m is void. Moreover, crack extension resistance curve J-Δa was established for monitoring the energy absorbed by crack initiation and propagation, which implicates the toughness property of HSLA under dynamic loadings.

As above, quasi static tensile, impact tensile and instrumented Charpy impact testing are integrated into the unique experimental platform, on which the overall assessment of material strength, plasticity and toughness properties could be accomplished with the strain loading rate from 10^{-2}-10^2 /s and various simulated loading conditions such as tensile or impact.

References

1. Kobayashi T, Yamamoto I, Niinomi M., “Introduction of a New Dynamic Fracture Toughness Evaluation System,” J. of Testing and Evaluation, JTEVA, **21**, 145-153 (1993).
2. Server W.L., “General Yield of Charpy V-Notch and Precracked Charpy Specimens,” J. Engng. Mat. Technol., Trans. ASME, **100**, 183-188 (1978).
3. Fang J, Ding F.L., Wang CZ., “Experimental Study on the Material Dynamic Fracture Properties by Instrumented Charpy Impact Test with Single Specimen Method,” J. Phys. IV France, **110**, 551-557 (2003).