

An Experimental Study on Mechanical properties of P110S under Dynamic Loads

LI Mingfei^{1,a}, CAO Lihu^{2,b}, GENG Hailong^{3,c}, LIU Junyan^{4,d}, DOU Yihua^{5,e}

¹ Lecturer School of Aeronautics, Northwestern Polytechnical University, School of Mechanical Engineering, Xi'an Shiyou University, in casing strength evaluation and perforating column mechanical analysis

² Tarim Oilfield, an engineer engaged in drilling, well completion and well integrity research and practice, now works at PetroChina Tarim Oilfield Oil and Gas Engineering Research Institute

³ Tarim Oilfield, an engineer engaged in oil well completion research and practice, now working in China Petroleum Tarim Oilfield Oil and Gas Engineering Research Institute

⁴ Tarim Oilfield, an engineer engaged in oil well completion research and practice, now working in China Petroleum Tarim Oilfield Oil and Gas Engineering Research Institute

⁵ Xi'an Shiyou University, in casing strength evaluation and perforating column mechanical analysis

^alimf88@126.com ^b caolh-tlm@petrochina.com.cn ^c genghailong1020@163.com
^d liujunycaolh-tlm@petrochina.com.cn ^e yhdou@vip.sina.com

Abstract. Oil country tubular goods (OCTG) may develop plastic bending, fracture and fatigue failure during the service due to dynamic loads, such as perforation impacts and fluid-induced vibration. This paper was to evaluate strength safety of OCTG under dynamic loading. To gain key parameters of the dynamic constitutive model of materials represented by Johnson-cook, an axial tensile test of the common P110S and an experiment on its mechanical properties under high strain rate were carried out for the first time. The yield limit of P110S under static loads was 775MPa, which was 2.2% higher than the nominal value (758MPa). The ultimate strength was 835MPa and the yield ratio was 1.08. Since it often requires the yield ratio higher than 1.25, the P110S had slightly poor tenacity. Under the strain rates of 500s⁻¹ and 1000s⁻¹, the yield limits of P110S were 15.5% and 41.4% higher than the static measured values. The dynamic loading experiments of P110S under the strain rates of 500s⁻¹ and 1000s⁻¹ were corresponding to the fluid-induced vibration of columns and perforation impacts-induced vibration of columns, respectively. Dynamic factor of P110S was determined according to engineering habits. According to conversion and contrast analysis on increment of yield limit under dynamic loading, the final strengths were decreased by 4.5% and 8.6%, respectively. Moreover, key parameters of the Johnson-cook dynamic constitutive model of P110S material were determined through experiments for the first time. They could provide key parameters of constitutive model for accurate finite element simulation analysis under dynamic loads.



1. Introduction

Oil country tubular goods (OCTG) are easy to develop breakage and bending of columns during the service due to the dynamic loads from perforation impacts and fluids, which have attracted high research attentions in the world^[1-3]. Gilat A et al. ^[4] developed a new experimental device that can measure the full-field deformation and temperature on sample surface in the high-speed tensile test. Gilat A et al. ^[5] measured strain and strain rates in compressive and tensile separation Hopkinson experiments by using the commercial image software and two digital high-speed cameras. Baumann C et al. ^[6] and Baumann C E et al. ^[7] calculated the instantaneous pressures of perforation fluid and the gun body by the computer software developed by Schlumberger, and predicted deformations, speeds, accelerations and stresses of tubular columns and downhole tools in the perforation segment. Some foreign companies (e.g. Schlumberger) took the perforation pressure analysis and measurement technologies as the core confidentialities. They only offered Chinese oil fields limited single well technological services rather than software and instrument. In addition, feasibility and applicability of associated studies still have to be further confirmed. All of these studies viewed OCTG as an integral bar, but overlooked influences of mechanical attributes and dynamic performances of OCTG on its overall stress.

In material sciences, studies concerning mechanical properties of materials under dynamic loads mainly focused on dynamic responses of high-energy and high-strength protective metals of ships and warships to explosive blast^[8-9]. They concluded that changes of strain rate and deformation temperatures influenced rheological stress of H13 steel significantly, and evident dynamic softening was developed, thus getting relevant parameters of Johnson-Cook model. Lindholm et al ^[10] described the development of high-speed torsion testing machine as well as strength related with copper strain rate under strong shear strain. The acquired test technologies and data were applied in ballistics and machining. Although there were many experiments on P110 materials, they mainly focused on static mechanical properties of P110 materials with different Cr contents as well as their resistances to CO₂ and H₂S corrosion behaviors. No experimental studies on P110S under dynamic loads have been available yet.

In a word, P110S was collected and processed into standard specimens for the standard tensile experiments. These experiments quantified the dynamic factor and increment of yield strength of the material under dynamic loads, gained key parameters of the dynamic Johnson-cook constitutive model and improved analysis precision of safety coefficient of columns under dynamic loads. Stress and strain values were mean of two groups of specimens. Hence, the stress-strain curves of P110S under static loads were gained. Material samples were collected on the same OCTG and processed into 15 $\Phi 5\text{mm} \times h 5\text{mm}$ solid cylinder samples. These cylinder samples were used in 15 groups of experiments on impact strain rates under 500s^{-1} and 1000s^{-1} , thus getting stress-strain curves under different high strain rates. Later, key parameters of the dynamic Johnson-cook constitutive model were determined by analyzing increment of yield strength and comprehensive dynamic load of P110S under high strain rates. Research conclusions could provide references to analyze strength safety of OCTG under dynamic loads.

2. Experimental analysis on stress-strain curves of P110S

Standard regulations on the size of tensile specimens were proposed for accurate comparison of properties of different materials. In this experiment, tensile specimens adopted the rectangular sections. According to requirements in internal standards of GB/T228-2002 and GB/P7314-1987, specimens shall meet the Eq.(1):

$$L_0 = 11.3\sqrt{S_0} \quad (1)$$

where L_0 is length of specimens (mm) and S_0 is the sectional area of rectangular specimens (mm²).

A total of 4 groups of specimens with different specifications were prepared (Figurea 1). The sectional area was $19.05 \times 9.19 \text{ mm}^2$ and the calculated L_0 was approximately equal to 150 mm. The clamping parts at two ends were 10 mm, respectively. The total length of specimens was 170 mm.

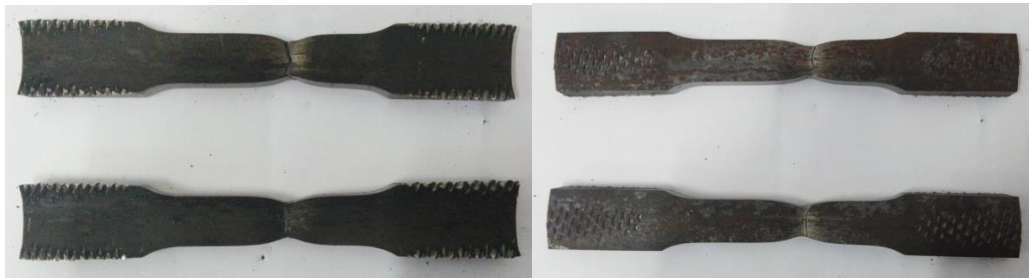


Figure 1. P110S specimens for axial tensile experiment

The static tensile experiment of P110S was accomplished on the axial tensile testing machine. To increase experimental accuracy and avoid errors brought by contingency of experimental data, four groups of same experiments were carried out. A total of 3,906 groups of data were recorded and extracted from each group of experiments. Some data are listed in Table 1. Mean values of four groups of experimental data were collected to draw the stress-strain curves of P110S (Figure 2 and Figure 3). Obviously, the yield limit of P110S was 775 MPa, which was 2.2% higher than the nominal value (758 MPa). The ultimate strength was $\sigma_b=835\text{MPa}$ and the yield ratio was $\sigma_b/\sigma_s=835/775=1.08$. With considerations to tenacity requirements of steel materials, it generally requires the yield ratio to be higher than 1.25 (GB50204-2002), indicating the slightly poor tenacity of P110S. Therefore, P110S is easier to develop “brittle failure” in actual working conditions.

Table 1. Some axial tensile experimental data of P110S

Data group	Time/S	Loads/kN	Displacement /mm	Deformation/mm	Stress/MPa
2238	106.03	139.25	13.65	2.20	795.41
2239	106.09	139.26	13.65	2.20	795.43
2240	106.13	139.27	13.66	2.21	795.54
2241	106.17	139.40	13.67	2.22	796.27
2242	106.23	139.42	13.68	2.23	796.36
2243	106.27	139.42	13.68	2.23	796.36
2244	106.31	139.40	13.69	2.24	796.27
2245	106.37	139.40	13.69	2.24	796.23
2246	106.41	139.40	13.69	2.24	796.23
2247	106.45	139.55	13.70	2.25	797.11
2248	106.51	139.66	13.71	2.26	797.75
2249	106.55	139.66	13.72	2.27	797.74

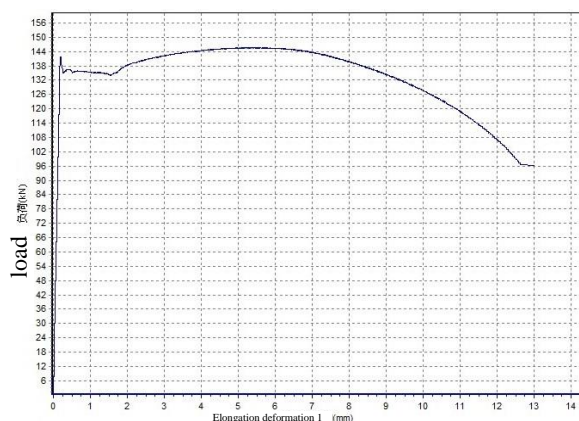


Figure 2. The relation curve between axial tensile loads and elongation deformation of P110S

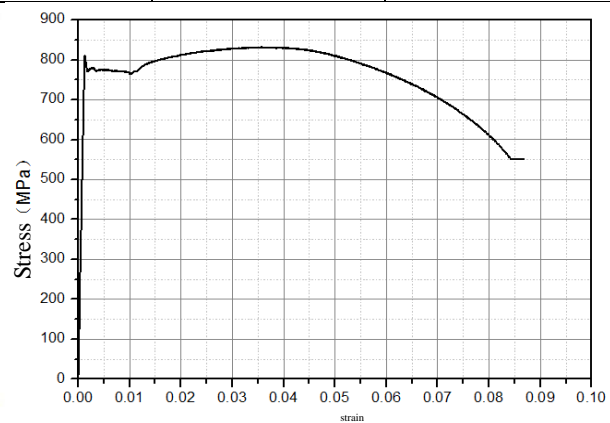


Figure 3. Axial tensile stress-strain curves of P110S

3. Experimental analysis on mechanical properties of P110S under dynamic loads with high strain rates

Samples were collected on the same P110S tube and processed into 15 $\Phi 5$ mm \times h5 mm solid cylinders. A total of 15 groups of simulation experiments on impact strain rates were carried out. Results are shown in Fig.4.



Figure 4. Specimens for impact experiments of P110S under high strain rate and dynamic loads

It is mainly used to test mechanical properties of metal materials under high strain rates of $10^2 \sim 10^4$ /s. Air pressure-driving bar impacted the input bar at a certain speed, thus generate compressive stress pulse in the input bar. When this compressive stress pulse was propagated into the contact surface between input bar and samples, some stress impulses were reflected to the input bar, while the rest transmitted to specimens. Impact loads were applied onto specimens until the failure. Incidence, reflected and transmitted pulse voltage signals were measured by strain gages pasted on the input bar and transmission bar, and then converted into strain signals. Subsequently, stress, strain and strain rate of specimens were acquired according to the one-dimensional stress wave theory^[11]:

$$\begin{aligned}\sigma_s &= E \left(\frac{A_b}{A_s} \right) \varepsilon_T \\ \varepsilon_s &= - \left(\frac{2C_0}{l_s} \right) \int_0^t \varepsilon_R dt \\ \dot{\varepsilon}_s &= - \left(\frac{2C_0}{l_s} \right) \dot{\varepsilon}_R\end{aligned}\quad (2)$$

where E is the elasticity modulus of high-strength steel pressure bar. C_0 is the elastic wave velocity of pressure bar. ε_T is the transmission strain signals which are generated by transmission wave and collected by strain gage on the transmission bar. ε_R is the reflection strain signals which are generated by reflected wave and collected by strain gage on the input bar. A_b and A_s are sectional areas of pressure bar and specimens. l_s is the length of specimens.

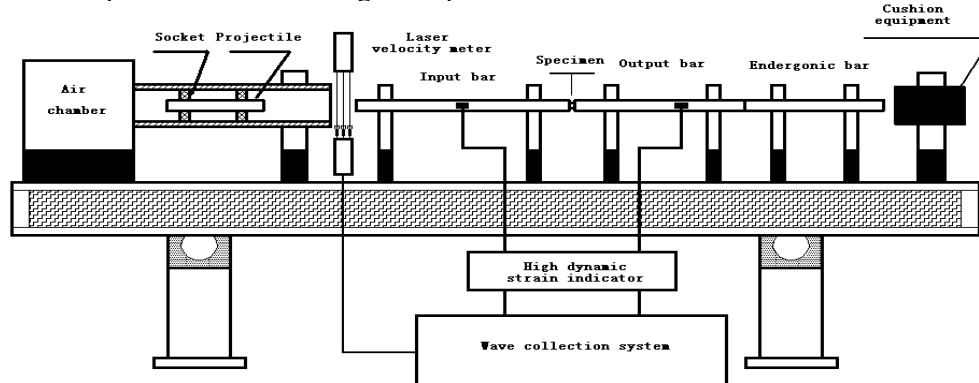


Figure 5. Structure of the Hopkinson pressure bar test device

Considering vibrations of tubular columns caused by perforation impacts and fluids, the strain rate ranged between 500s^{-1} and 1000s^{-1} . To avoid error caused by contingency of single experimental data, three specimens were set as one group and the acquired experimental data were the mean values. 2,166 groups of experimental data were recorded to improve experimental accuracy. Some data are listed in Table 2.

The stress-strain curves under different strain rates were drawn by using data (Figure 6). Clearly, two curves overlapped basically under the dynamic strain rate of 500s^{-1} . The mean yield limit (σ_s) of P110S was 895MPa, which was 15.5% higher than the static measured value (775MPa). The ultimate strength (σ_b) was 990MPa, which was 18.6% higher than the static measured value. Under 1000s^{-1} dynamic strain rate, three curves overlapped basically. The mean σ_s of P110S was 1,096MPa, which was 41.4% higher than the static measured value (775MPa). σ_b was 1,201MPa, which 43.8% was higher than the static measured value.

With respect to the stress-strain state, P110S belongs to the metal plastic flow under thermal activation mechanism when the strain rate is lower than $10,000\text{s}^{-1}$. The strain rate and temperature follow the Arrhenius equation^[10]:

$$\dot{\varepsilon}_p = \dot{\varepsilon}_0 \exp \frac{-\Delta G(\tau, T)}{kT} \quad (3)$$

Table 2. Test results of mechanical property of P110S under high dynamic strain rate

Stress/ MPa	Strain	Stress/ MPa	Strain	Stress/ MPa	Strain	Stress/ MPa	Strain	Stress/ MPa	Strain
500s-1		500s-1		1000s-1		1000s-1		1000s-1	
84.762	0.082	106.036	0.188	219.307	0.190	92.977	0.196	102.469	0.075
82.975	0.082	107.459	0.188	218.871	0.190	92.375	0.196	102.836	0.075
82.245	0.082	106.451	0.188	217.580	0.190	92.070	0.196	100.896	0.075
79.950	0.082	104.795	0.188	218.634	0.190	91.713	0.196	101.193	0.075
79.338	0.082	105.449	0.188	215.687	0.190	89.909	0.196	100.612	0.075
78.025	0.082	103.936	0.188	212.663	0.190	91.801	0.196	99.915	0.075
77.705	0.082	101.449	0.188	214.089	0.190	91.295	0.196	101.908	0.075

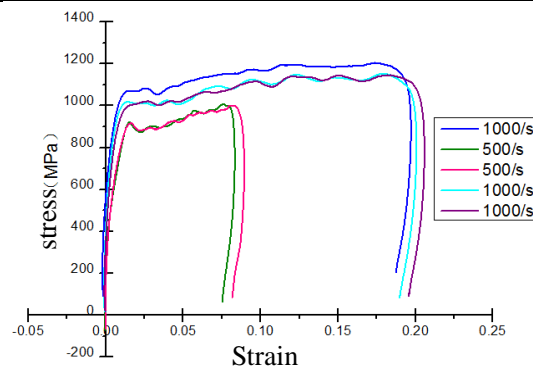


Figure 6. Stress-strain curves of P110S under different strain rates

4. Determination of dynamic factor of P110S under high strain rate and analysis of safety factor

Due to dynamic loads caused by perforation impacts and fluid, P110S often will induce vibration and shaking of tubular columns. How to determine the dynamic factor in these two situations is a complicated problem with abundant influencing factors. Without studies on dynamic load related with vibration of OCTG, the author has reviewed abundant literatures. The dynamic factor table of mechanical equipments in the Handbook of Mechanical Design is relatively authoritative. In this table, dynamic factors of 48 ordinary machines are listed. Specifically, the dynamic factor of 19 machines ranges between 1.2-1.5 and the dynamic factor of 29 machines ranges within 2.0-5.0. Dynamic coefficients for reference are listed in Table 3. With consideration to both situations, the upper limit of

slight impacts (1.20) could be applied to test tubular column vibration induced by fluid. The middle value (1.5) in 1.2-1.8 is used to test vibration of tubular columns caused by perforation impacts.

The dynamic loading experiment of P110S under the strain rate of 500s^{-1} tested the tubular column vibration induced by fluid. The increase coefficient of yield limit and dynamic factor were measured 1.155 and 1.200, respectively. Therefore, strength was decreased by 4.5% compared with that under static loads. The dynamic loading experiment of P110S under the strain rate of 1000s^{-1} tested the column vibration induced by perforation impacts. The increase coefficient of yield limit and dynamic factor were measured 1.414 and 1.50, respectively. This implied that strength was 8.6% lower than that under static loads.

Table 3. Dynamic factors of ordinary steel materials under different working conditions

Loading characters	Dynamic factors	Common application ranges
Slight impacts	1.0-1.2	Motor, turbine, ventilator and water pump
Moderate impacts or moderate inertia force	1.2-1.8	Vehicles, power machinery, crane, paper machine, metallurgical machinery, concentrating machine, winch, machine tool.
Strong impacts	1.8-3.0	Crusher, rolling mill, sounding borer

5. Determination of parameters of the Johnson-Cook model of P110S under high dynamic strain rate

The Johnson-cook thermoviscoplasticity dynamic constitutive model which is constructed based on abundant practical experiences is applicable to a large range, especially metal materials represented by steel. It can reflect the dynamic constitutive relations of metals under large strain, high strain rate and high-temperature loading. The flow stress of Johnson-Cook can be expressed as^[12]:

$$\sigma = [A + B(\varepsilon^P)^n](1 + C \ln \dot{\varepsilon}^1)(1 - T^{*m}) \quad (4)$$

where ε^P is the equivalent plastic strain. $\dot{\varepsilon}^1$ is the equivalent plastic strain rate when $\varepsilon=1$. T^* is the

$$T = \frac{T - T_r}{T_m - T_r}$$

relative temperature and $T = \frac{T - T_r}{T_m - T_r}$. Items in the first brackets are influencing factors of strain and items in the second brackets are influencing factors of strain rate. Items in the third brackets are influencing factors of ambient temperature. T_r is the reference temperature, which is determined the room temperature 293K in this test. T_m is the temperature at melting point of OCTG, which is set 1800K. A, B, N, C and m are five key material constants of the model. Key parameters of the Johnson-Cook model of P110S are gained in the experiment under high dynamic strain rate (Table 4).

Table 4. Values of Johnson-Cook model of P110S

Undetermined parameters	A/MPa	B/MPa	n	C	m	T_r /K	T_m /K
Numerical values	1120	550	0.31	0.02	1.08	293	1953

6. Conclusions and suggestions

In this paper, an axial tensile experiment of $\Phi 88.9 \times 6.45$ mm P110S under static loads and an experiment on its mechanical properties under high strain rate are carried out successively. On this basis, the overall mechanical properties of P110S are analyzed. Some major conclusions could be drawn.

(1) The first stress-strain curve of P110S which is one of the widely used OCTG in onshore oil fields in China is carried out, which provides the first-handed data concerning axial tensile mechanical properties of OCTG. The dynamic performance of P110S under high dynamic strain rate is performed by using the Hopkinson pressure bar system. Therefore, the first-handed experimental data on stress-strain relationship of P110S under dynamic loads are acquired.

(2) The yield limit of P110S is 775MPa, which is slightly (2.2%) higher than the nominal value

(758MPa), indicating the qualified strength of P110S. The ultimate strength is 835MPa and the yield ratio is 1.08, which is lower than the requirements of steel tenacity (yield ratio >1.25). This reflects the slightly poor tenacity of P110S and it is easy to develop “brittle failure”.

(3) Under the dynamic strain rate of 500s^{-1} , the yield limit (σ_s) of P110S is 15.5% higher than the static measured value. Under the dynamic strain rate of 1000s^{-1} , σ_s of P110S is 41.4% higher than the static measured value.

(4) The dynamic load experiment of P110S under the dynamic strain rate of 500s^{-1} tests tubular column vibration induced by fluid and strength of P110S is 4.5% lower. The dynamic load experiment of P110S under the dynamic strain rate of 1000s^{-1} tests tubular column vibration induced by perforation impacts and the strength of P110S is decreased by 8.6%.

(5) Seven key parameters of the Johnson-cook dynamic constitutive model are acquired by experiments for the first time. The first Johnson-cook dynamic constitutive model of P110S is constructed. These can provide references to increase strength safety analysis accuracy of tubular columns under dynamic loads.

Acknowledgments

Fund Project: National Natural Science Fund for Shale Gas Horizontal Well Fracturing and Production Casing Deformation Mechanism and Control Mechanism Research (51674199).

References

- [1] Zhang Wei, Xu Cheng, Li Mingfei, et al. Transient Response and Stress Intensity Analysis of Tubular Columns in the Perforation Segment [J]. Petroleum Machinery, 2017, 45(11):90-94.
- [2] Dou Yihua, Li Mingfei, Zhang Fuxiang et al. Analysis of Impacts of Well Structure on Strength Safety of Tubular Columns in the Perforation Segment [J]. Petroleum Machinery, 2012(3):27-29.
- [3] Carlos Baumann, Harvey Williams. Perforating High-Pressure Deepwater Wells in the Gulf of Mexico[C]. SPE146809, 2011:1-13.
- [4] Gilat A, Kuokkala V T, Seidt J, et al. Full-Field Temperature Measurement in High Strain Rate Tensile Experiment[C]// International Conference on Impact Loading of Structures and Materials. 2016.
- [5] Gilat A, Schmidt T E, Walker A L. Full Field Strain Measurement in Compression and Tensile Split Hopkinson Bar Experiments[J]. Experimental Mechanics, 2009, 49(2):291-302.
- [6] Baumann C, Williams H, Korf T, et al. Perforating High-Pressure Deepwater Wells in the Gulf of Mexico[C]// 2011.
- [7] Baumann C E, Bustillos E P, William A, et al. Reduction of Perforating Gunshock Loads[J]. Spe Drilling & Completion, 2011, 27(1).
- [8] Shao J J, Zhai D M, Hou D W, et al. EXPERIMENTAL RESEARCH ON STRESS AND STRAIN OF WARSHIP MODEL INDUCED BY UNDERWATER EXPLOSION[J]. Engineering Blasting, 2012.
- [9] Davis S, Borchers J A, Maranville B B, et al. Fast strain wave induced magnetization changes in long cobalt bars: Domain motion versus coherent rotation[J]. Journal of Applied Physics, 2015, 117(6):2731.
- [10] Lindholm U S, Nagy A, Johnson G R, et al. Large Strain, High Strain Rate Testing of Copper[J]. Journal of Engineering Materials & Technology, 1980, 102(4):376.
- [11] Ripperger E A, Jr H W. The Relationship Between the Constitutive Equation and One-Dimensional Wave Propagation[M]// Mechanical Behavior of Materials under Dynamic Loads. Springer Berlin Heidelberg, 1968:1088-9.
- [12] Gambirasio L, Rizzi E. On the calibration strategies of the Johnson-Cook strength model: discussion and applications to experimental data[M]// Sources of the Confucian tradition :. Shandong Friendship Press, 2014:704-715.