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Determination of 40Cr Johnson–Cook Dynamic Constitutive Equation for Cold roll-beating Forming Process

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As a near net-shape advanced manufacturing technology, cold roll-beating is a dieless unconstrained incremental forming technology. For the features of the forming process, it is necessary to study the forming mechanism under thermal–mechanical coupling conditions, thus it is very significant to investigate the mechanical properties of material under high temperature and high strain rate. To explore the forming mechanism of the cold roll-beating forming technology, 40Cr quenched and tempered steel dynamic compression experiments used a separate SHPB system. Dynamic compression tests and static compression experiments under different conditions were carried out. Based on the experiment analysis, the strain hardening coefficient, the strain rate sensitivity coefficient, and the thermal softening coefficient were determined, thus the Johnson–Cook dynamic constitutive equation for 40Cr was built, which can provide theoretical basis for further study of the thermal–mechanical coupling effects of 40Cr cold roll-beating forming process.

1. Introduction

With increasingly drastic marketing competition and the rapid updating of products, many drawbacks associated with the traditional die forming process are reflected day by day, such as long production preparation time, large tonnage equipment, poor processing flexibility and high manufacturing costs. Because of the excellent features of part production, various advanced precise plastic forming technologies become important research frontiers in modern technology. Technology of light-weight, rapidness, flexibility and precision is one of the main research targets in the new plastic forming field (Hamiltona. K and Jeswiet .J (2010); Neugebauera. R, et al. (2011); Merkleina. M, et al (2012)).

As a near net-shape advanced manufacturing technology, cold roll-beating is paid more and more attention (Cui F. K., et al (2012)). Krapfenbauer (1984, 1994) proposed a new cold roll-beating technique called the Grob method, in which two pairs of rollers eccentrically mounted strike the workpiece surface and form gears or splines with the help of indexing motion. At present, the western countries have cold roll-beating machine tools, high-speed cold roll forming technology, and research results from conducted studies. However, few reports exist based on the core technology. Currently, the roller design theory, kinematics, dynamics, forming mechanisms, and other aspects of high-speed cold roll-beating forming technology were mainly studied by Cui F K (2006, 2008, 2012) and Li Y (2011, 2012, 2013, 2014). However, study of cold roll-beating is still in the exploration and development stage, the system has not yet formed for the theory and practice.

In the high-speed cold roll-beating forming process, the forming tool impacts the workpiece material at a high speed instantly. The transient effects of the applied force result in energy dissipation in a local area and invariably lead to instant generation of large material strains. The workpiece material at high strain and high strain rates and the severe tribological behaviour between the tool and the workpiece elicit a strong thermal-mechanical multi-field coupling effect (Xiong Qi-Lin and Tian Xiao-Geng (2015), He K. F. (2015)). It is necessary to study the forming mechanism under thermal–mechanical coupling conditions. To investigate the mechanical properties of material under high temperature and high strain rate during cold roll beating process is of great significance. These studies focused on three aspects: the thermal-mechanical coupling forming mechanism macro and micro theoretical modelling , thermal-mechanical coupled finite element analysis of

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thermoplastic formation and microscopic experimental analysis of thermoplastic formation metal, which provided research ideas for formation mechanism of the thermal-mechanical coupling in the cold rolling forming process.

Cold rolling forming process generated thermal effect which causes the surface and internally generated non-uniform temperature field, which affects metal flow in the workpiece forming process, eventually have an impact on the quality and performance of formed parts. So it is necessary to study the forming mechanism under thermal coupling in the high-speed cold rolling forming process. In this paper, combined theoretical analysis, numerical simulation and experimental study. On the basis of establishing 40Cr quenched and tempered steel J-C dynamic constitutive equations, studying forming mechanism under thermal-mechanical coupling of high-speed cold rolling in order to improve using performance and surface quality of the cold rolling forming parts.

In this paper, the constitutive equation of 40Cr for cold roll-beating process was established; the Hopkinson pressure bar tests were carried out. Based on the experiments, the corresponding coefficients were determined and the Johnson–Cook dynamic constitutive equations for 40Cr were identified.

2. Principle of Cold Roll-beating Forming

High speed precision cold roll-beating is typical of precise plastic forming technology. During the forming process, by taking advantage of the inherent plasticity of rough material at ordinary temperatures, a roller of a certain shape and rotating at high speeds roll-presses and beats the rough blank intermittently, forcing the local metal of the rough surface to flow, and plastic deformations to accumulate in order to form the profile of the required part.

The working principle of cold roll-beating is shown in Figure 1. The rollers of certain shapes are mounted on a rotating shaft that moves evenly at high speeds. During the cold roll-beating forming, the slab blank feeds horizontally, and the rollers, moving at high speed rotations, beat the slab blank intermittently; afterward, the metal material of the slab blank surface moves a certain displacement due to high speed impact of the rollers. The roller rotates around its own axis the moment the roller comes in contact with the slab as a result of the friction between them, thereby ensuring the rolling between the roller and the slab. The action is repeated until the specific shape is formed in the slab blank to satisfy the predetermined depth of cut (rolling reduction).

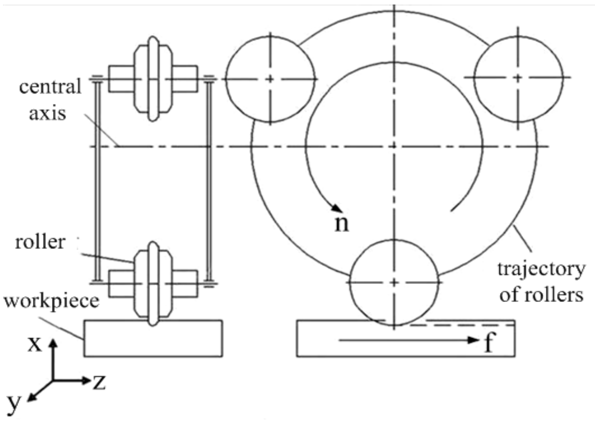


Figure 1: Principle of cold roll-beating forming

3. Establishing the constitutive equation

The establishment of constitutive relations depends on the comprehensive influence of hardening, strain rate, and temperature on the flow stress. Flow stress can be expressed as a function of plastic strain, temperature, and strain rate, and is usually expressed by the following equation:

$$\sigma(\varepsilon, \dot{\varepsilon}, T) = \sigma_0(\varepsilon, \dot{\varepsilon}, T)\, g(\dot{\varepsilon}, T)\, h(T) \tag{1}$$

Where $\sigma_0(\varepsilon, \dot{\varepsilon}, T)$ describes the yield stress and hardening under reference temperature and specific strain rate, $g(\dot{\varepsilon}, T)$ describes the temperature dependency on strain rate, $h(T)$ describes the effect of temperature.

The Johnson–Cook (J-C) model is an empirical viscoelastic constitutive equation that can better describe the effect of hardening, strain rate, and temperature on materials at high strain rates and has been widely used for various engineering applications (SAMANTARAY. D, et al. (2009), Wu Horng-yu, et al. (2013)) The Johnson–Cook flow stress expression is given by the following equation:

$$\sigma = \left[A + B\left(\varepsilon^p\right)^n\right]\left[1 + C\ln\left(\dot{\varepsilon}\right)^*\right]\left[1 - \left(T^*\right)^m\right] \quad (2)$$

where $T^* = \frac{T - T_r}{T_m - T_r}$, $\dot{\varepsilon}^* = \frac{\dot{\varepsilon}^p}{\varepsilon_0}$, σ is the flow stress, ε^p is the equivalent plastic strain, A is the yield stress, B is the strain hardening coefficient, n is the strain hardening exponent, m is the temperature sensitivity coefficient, T is the experimental temperature, T_m is the melting point, T_r is the reference temperature, T_r=20°C, $\dot{\varepsilon}_0$ is the reference strain rate, $\dot{\varepsilon}_0 = 0.004s^{-1}$, $\dot{\varepsilon}^p$ is the equivalent plastic strain rate, $\left[A+B\left(\varepsilon^p\right)^n\right]$ is the strain hardening effect, $\left[1+C\ln\left(\dot{\varepsilon}\right)^*\right]$ is the strain rate effect, and $\left[1-\left(T^*\right)^m\right]$ is the temperature softening effect.

4. Determination of constitutive equation coefficients

4.1 Experimental analysis

The Johnson–Cook model parameters must be obtained experimentally using the MTS testing machine. The experimental material is 40Cr quenched and tempered steel. The sample size is Φ = 5 mm × 4 mm, with a parallelism between the two end-surfaces of 0.002, and a hardness HRC value ranging between 26–30.

In order to analyze the effects of strain rate, temperature, and hardening on the flow stress response of 40Cr quenched and tempered steel, five groups of dynamic compression experiments and one group of static compression experiments were conducted. Dynamic compression tests were conducted on three groups with strain rate values of 1072 s-1, 2534 s-1, and 5160 s-1, respectively, at room temperature. The other two groups were studied at high temperatures with strain rates of 1193 s-1 (200°C) and 1380 s-1 (400°C), respectively. Static compression experiments were conducted at room temperature and at a selected strain rate of 0.004 s-1.

The maximum axial load of the testing machine was 250 KN. The 40Cr quenched and tempered steel dynamic compression experiments used a separate SHPB system. The SHPB equipment is shown in Figure 2, including the striker rod (bullet), input lever (incident bar), and output rod (transmission lever). In the device, the striker rod, the input rod, and the output rod are made of the same material and have the same diameter. Under the same elastic state, both rods have good concentricity.

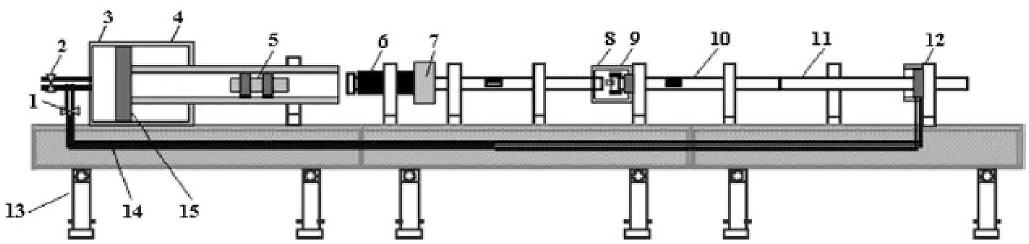
Four basic assumptions were made in reference to the separate SHPB bar system, namely that:

① one-dimensional stress wave theory can be applied to study the bar system,

② sample deformation uniformity applies,

③ inertial effects can be ignored,

④ the friction between the sample and struts can be ignored.



1- Exhaust valve; 2- intake valve; 3- back cavity; 4- front chamber; 5 - hitting rod; 6- input rod; 7- reaction bodies; 8- furnace and thermocouples; 9-specimens; 10- output rod; 11- absorbing rods; 12- drive; 13- supports; 14- air pipe; 15- pistons.

Figure 2: Schematic representation of the Hopkinson pressure bar system

4.2 Determination of parameters

The values of A, B, and n must be estimated based on the experimental data under room temperature conditions. Under a reference temperature condition (T = 20°C) and a reference strain rate of $(\dot{\varepsilon} = 0.004)$, the J-C equation becomes,

$$\sigma = A + B\varepsilon^n \quad (3)$$

Applying the logarithm on both sides of this equation,

$$\ln(\sigma - A) = \ln B + n \ln \varepsilon \quad (4)$$

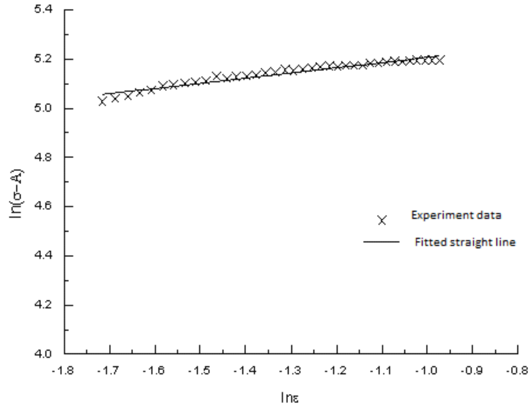


Figure 3: The relationship between lnε and ln(σ-A)

Where B is the intercept of the line, and n is slope. In equation (2), A with the value of $\sigma_{0.085}$ = 905 MPa. Under room temperature and static compression conditions $(\dot{\varepsilon} = 0.004, T = 293K)$, a linear least squares method was used to fit the experimental data to a straight line. Based on the fitted straight line, the correlation coefficient (R2) was 0.94, n = 0.21, and B = 226 MPa. The plot of equation (4) is shown in Figure 3.
In order to determine the strain rate sensitivity coefficient C, the experimental data on dynamic compression is needed. Under the reference temperature (T = 20°C) condition, the J-C equation becomes,

$$\sigma = \left(A + B\varepsilon^n\right)\left(1 + C \ln \dot{\varepsilon}^*\right) \Rightarrow \frac{\sigma}{A + B\varepsilon^n} = 1 + C \ln \dot{\varepsilon}^* \quad (5)$$

Where C is the slope of the line relating $\left[\sigma / \left(A + B\varepsilon^n\right) - 1\right]$ and $\ln \dot{\varepsilon}^*$ based on equation (5). Astraight line was fitted based on the test values of true stress for the chosen strain rate values of 632 s-1, 1072 s-1, and 5167 s-1 while the strain value is 0.1, as shown in Figure 4. Elicited results yielded a value of C = 0.03.

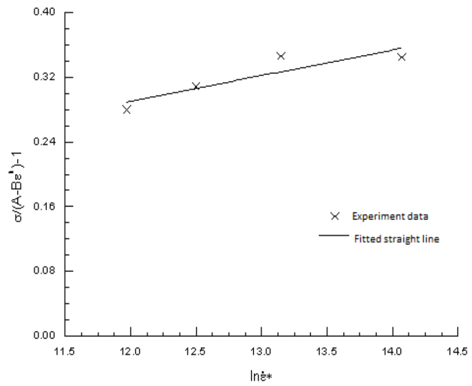


Figure 4: Relationship between $\ln \dot{\varepsilon}^*$ *and* $\left[\sigma / \left(A + B\varepsilon^n\right) - 1\right]$

The thermal softening coefficient refers to the flow stress dependence on the deformation temperature. Solution for parameter m needs use of the dynamic compression test data, under high temperature, and at reference temperature and strain rate conditions. The J–C constitutive equation is obtained upon application of the logarithm on both sides of eq (2), resulting in the linearized expression of the following equation:

$$\ln\left[1-\frac{\sigma}{\left(A+B\varepsilon^{n}\right)\left(1+C\ln\frac{\dot{\varepsilon}}{\varepsilon_{0}}\right)}\right]=m\ln T^{*} \tag{6}$$

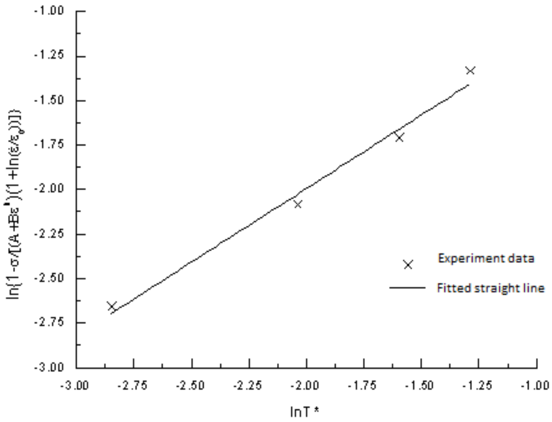


Figure 5: Relationship between lnT and* $\left\{1-\sigma\Big/\left(A+B\varepsilon^{n}\right)\left(1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right)\right\}$

Where m is slope of the line. Choosing the strain rates of 1124 s-1, 1193 s-1, 1236 s-1, and 1380 s-1, the corresponding temperatures are 100°C, 200°C, 300°C, and 400°C, with strain value of 0.1, the test values of true stress are obtained. Then, using the same software and fitting methodology as that described previously, the fitted straight line is shown in Figure 5, a value of m = 0.83 was estimated.
Integration of the J-C constitutive equation that was initially solved for its parameter data results in the constitutive flow stress expression for 40Cr, as described by the following equation:

$$\sigma=\left(905+226\varepsilon^{0.21}\right)\left(1+0.03\ln\frac{\dot{\varepsilon}}{0.004}\right)\left[1-\left(T^{*}\right)^{0.83}\right] \tag{7}$$

5. Conclusions

In the cold roll-beating forming process, the produced thermal effect affects the metal flow and eventually has an impact on the quality and performance of the formed parts. It is therefore necessary to study the forming mechanism of the cold roll-beating forming process under thermal–mechanical coupling conditions. Thus it is very significant to investigate the mechanical properties of material under high temperature and high strain rate during the forming process.
The 40Cr quenched and tempered steel dynamic compression experiments used a separate SHPB system. Dynamic compression tests were conducted with strain rate values of 1072 s-1, 2534 s-1, and 5160 s-1, respectively, at room temperature, while the other two groups were studied at high temperatures with strain rates of 1193 s-1 (200°C) and 1380 s-1 (400°C), respectively, static compression experiments were conducted at room temperature and at a selected strain rate of 0.004 s-1. Based on the experiment analysis, the strain hardening coefficient, the strain rate sensitivity coefficient, and the thermal softening coefficient were determined, thus the J–C dynamic constitutive equations for 40Cr have been identified..
The dynamic constitutive model presented in this paper can effectively predict plastic flow stress for 40Cr quenched and tempered steel under different temperatures, research in this paper can provide the theoretical basis for the further assessment of the thermal–mechanical coupling effects of 40Cr high-speed cold roll-beating forming process.

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References

Cui F. K., Zhu W. J., Wang X. Q., 2012, Current research and development trends of high speed cold rolling technology. Journal of Henan Polytechnic University, 31(2):191-195.

Cui F. K., Li Y., Zhou Y. W., 2006, Technologic Research on Rolling Involute Spline axis. Journal of Agricultural Machinery, 37(12): 189-192.

Hamiltona. K, Jeswiet J., 2010, Single point incremental forming at high feed rates and rotational speeds: Surface and structural consequences. Manufacturing Technology, 59(1):311-314. DOI: doi:10.1016/j.cirp.2010.03.016.

He K. F., Zhang Z. J. 2015, Thermodynamic characteristics analysis of aluminium welding process. Materials research innovations, 19(4): 89-93, DOI: 10.1179/1432891715Z.0000000001375

Krapfenbauer H., 1984, New aspects for the mass production of spur gears by cold rolling. IPE International Industrial & Production Engineering, 8(3): 39-41.

Krapfenbauer H., 1994, New methods to cold roll splines on hollow blank. European Production Engineering, 1(9):39-43.

Merkleina M., Allwoodb J. M., Behrensc. B. A, 2012, Bulk forming of sheet metal, CIRP Annals - Manufacturing Technology, 61(2): 725–745.

Neugebauera R., Bouzakisb K. D., Denkenac B., 2011, Velocity effects in metal forming and machining processes. CIRP Annals - Manufacturing Technology, 60(2): 627–650,DOI:10.1016/j.cirp.2011.05.001.

Quan J. H., Cui F. K., Yang J. X., 2008, Numerical Simulation of Involute Spline Shaft's Cold-rolling Forming Based on ANSYS/LS-DYNA. China Mechanical Engineering, 19(4): 419-422.

Samantaray D., Mandal S., Bhaduri A. K., 2009, A comparative study on Johnson Cook, modified Zerilli-Armstrong and Arrhenius-type constitutive models to predict elevated temperature flow behaviour in modified 9Cr-1Mo steel. Computational Materials Science, 47(2), 568-576, DOI: 10.1016/j.commatsci.2009.09.025.

Wu H. Y., Yang J. C., Zhu F. J., Wu C. T., 2013, Hot compressive flow stress modeling of homogenized AZ61 Mg alloy using strain-dependent constitutive equations. Materials Science and Engineering, 565(10):1-9. DOI:10.1016/j.msea.2013.03.005.

Xiong Q. L., Tian X. G., 2015, Thermomechanical Interaction in Metal Films during Ultrashort Laser Heating. Mechanics of advanced materials and structures, 22 (7), 548-555, DOI: 10.1080/15376494.2013.82881.

Yang M. S., Li Y., Yuan Q. L., 2013, A Hybrid Method to Deformation Force of High-speed Cold Roll-beating Forming. Journal of Digital Information Management, 11(2): 146-153.

Yuan Q. L., Li Y., Yang M. S., 2014, Research on Deforming Force of Slab Cold Roll-beating. China Mechanical Engineering, 25(2): 251-256.

Zhang L., Li Y., Yang M. S., 2011, Recent Development of Incremental Forming. Aerospace Materials & Technology, (06): 32-38.

Zhang L., Li Y., Yang M. S., 2012, Study on Metal Flowing of Lead Screw Cold Roll-beating Forming. China Mechanical Engineering, 23(13): 1623-1628.