Article

Dynamic Behaviors and Microstructure Evolution of Iron–Nickel Based Ultra-High Strength Steel by SHPB Testing

Hongge Fu 1,2, Xibin Wang 1, Lijing Xie 1,*, Xin Hu 1, Usama Umer 3, Ateekh Ur Rehman 4, Mustufa Haider Abidi 3 and Adham E. Ragab 4

1 Beijing Institute of Technology, School of Mechanical Engineering, Beijing 100081, China; fhg800922@163.com (H.F.); cutting0@bit.edu.cn (X.W.); 13810438099@163.com (X.H.)
2 North China Institute of Aerospace Engineering, School of Mechanical and Electrical Engineering, Langfang 065000, China
3 Advanced Manufacturing Institute, King Saud University, Riyadh 11421, Saudi Arabia; uumer@ksu.edu.sa (U.U.); mabidi@ksu.edu.sa (M.H.A.)
4 Industrial Engineering Department, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia; arehman@ksu.edu.sa (A.U.R.); aragab@ksu.edu.sa (A.E.R.)
* Correspondence: rita_xie2004@163.com

Received: 3 December 2019; Accepted: 22 December 2019; Published: 31 December 2019

Abstract: Iron–nickel based ultra-high strength steel (wt. 18–20% Ni) is characterized by its high strength and low thermal conductivity, and is normally used to make key components by forming and machining processes. The optimization of these processes is based on a deep understanding of the mechanical and dynamic behaviors under high strain, high strain rate, and high temperature. In this paper, the relationship of stress to strain, strain rate, and temperature is systematically investigated by the dynamic compression tests combined with quasi-static compression tests, and the hardening and softening is associated with the transformation in microstructures. According to the analysis, dynamic recrystallization around 600 °C is assumed to be one important influencing factor, hence hot deformation equations are established and the critical strain for dynamic recrystallization and the volume fraction of the dynamic recrystallized grains are defined.

Keywords: dynamic behavior; dynamic recrystallization; iron–nickel based ultra-high strength steel; microstructure; SHPB

1. Introduction

Iron–nickel based ultra-high strength steel (wt. 18–20% Ni) is a kind of low carbon Fe-Ni martensite steel with inter-metallic compound precipitated and hardened by aging treatment. It is used in a wide variety of applications in transportation industries owing to its unique comprehensive mechanical properties, i.e., ultra-high strength up to 2.2 GPa, good plasticity and toughness, high hardness, excellent fatigue resistance and low crack propagation rate [1–4]. While due to the high nickel content, it has very low thermal conductivity. Therefore, the machining of parts in the production is very difficult and often accompanied by high cutting force, high temperature, serious tool wear, and dangerous long chips.

In general, the performance of key components is determined by the surface and sub-layer, which is normally formed from the machining processes. In many cases, the mechanical behavior of the surface and sub-layer is strongly sensitive to the machining processing parameters, and sometimes this strong sensitivity may result from solid-state phase transformation, dynamic recrystallization, and recovery. In order to explore the mechanical response of materials and the change of the microstructure in high speed cutting, it is necessary to know the mechanical
deformation behaviors and microstructure evolutions under extreme loading conditions. At present, the research on ultra-high strength steel mainly focuses on the use and heat treatment [5–12]. The dynamic responses and accompanied metallographic transformations under extreme loading condition of high strain rate, large strain, and high temperature as in the machining process are waiting discovery.

Tests for the study on mechanical properties mainly include: (1) creep testing machines for loading at a strain rate of 0–10^−5 s^−1, (2) Cam plasticity machine and drop weight tests for strain rates below 500 s^−1, (3) The Split Hopkinson Pressure Bar (SHPB) for 10^2 s^−1–10^4 s^−1, (4) gas gun explosive and driven plate impact for strain rate above 10^4 s^−1. Amongst, SHPB technique is a widely used method for investigating the mechanical properties of materials at high strain rate [13–15], although it is tested that Gleebe 3800 equipped with Hydrowedge can reach a strain rate of 10^6 s^−1 when compressing a 1 mm-thick sample. In this study, the SHPB technique has been used to determine the dynamic behaviors of iron–nickel based ultra-high strength steel under the impact compressive loading conditions of strain-rates ranging from 10^3 s^−1 to 10^4 s^−1 and temperatures from 25 °C to 1200 °C, and furthermore the microstructures of the samples after compression are observed and analyzed. The plasticity and toughness of the iron–nickel based ultra-high strength steel are so high that they are very close to those of the pressure bars in SHPB test. This often brings some difficulties in the test especially at high strain rate. Two shims with much higher strength are added at both ends of the sample.

2. Mechanics and Dynamics Test Scheme

2.1. Material

The existence of alloy elements Ni, Mo, and C, etc., in iron–nickel based ultra-high strength steel in Table 1 plays important role in material strengthening. Its physical and mechanical properties are shown in Table 2. After solid solution treatment, air cooling, and aging, the metallographic structure of ultra-high strength steel is characterized by a high density of dislocations and single-phase Fe-Ni lath martensite structure [3], as shown in Figure 1.

| Element | C   | Ni | Mo | Ti  | Al  | Cr  | Si |
|---------|-----|----|----|-----|-----|-----|----|
| Content (wt. %) | ≤0.01 | 18–20 | 2.75–3.25 | 1.2–1.6 | 0.05–0.15 | ≤0.5 | ≤0.1 |

Table 1. Chemical composition of 18Ni maraging steel.

| Properties | Values |
|------------|--------|
| Density (g/cm^3) | 8.8 |
| Melting temperature (°C) | 1700 [16] |
| Tensile Strength (MPa) | 1800 [16] |
| Elongation at Break (%) | 12 [16] |
| Modulus of elasticity (GPa)/25 °C | 186 [16] |
| Coefficient of thermal conductivity (W/(m·K))/25 °C | 18.41 [16] |
| Specific heat (J/(g·K)) | 0.498 [16] |
| Hardness (HRC)/25 °C | 50–54 [16] |

Table 2. Mechanical and thermal properties of iron–nickel based ultra-high strength steel.
2.2. The Quasi-Static Compression Test

Quasi-static compression tests are carried out with a CRIMS electronic universal testing machine DNS-100. And in these tests, φ2 mm × 2 mm cylindrical samples are individually compressed at room temperature and three different strain rates of 0.01, 0.001, and 0.0001 s⁻¹. Each sample is compressed to 50%. The tests under each condition are repeated at least three times. Then the samples from the tests are polished with sandpapers and aluminum oxide suspension, and etched with electrolysis corrosion of 10% Cr₂O₃ water solution. The microstructures at the center are examined by a Leica DMI5000M Inverted metallographic microscope (Leica, Wetzlar, Germany).

2.3. Dynamic Compression Test

Dynamic behavior of iron–nickel based ultra-high strength steel at the temperature ranging from 25 °C to 1200 °C and strain rates from 10³ s⁻¹ to 10⁴ s⁻¹ is investigated by SHPB tests invented by H. Kolsky [17]. The SHPB device (Northwestern Polytechnical University, China) is equipped with a temperature-controlling system developed by Li et al. [18], as shown in Figure 2. And the stress–strain response is correlated with temperature and strain rates [19]. The SHPB test was conducted at Northwestern Polytechnical University.

Two sample sizes are used in the SHPB tests, φ4 mm × 4 mm cylindrical samples for lower strain rates of 500 s⁻¹, 1000 s⁻¹ and 2000 s⁻¹, while φ2 mm × 2 mm ones for higher strain rate of 4000 s⁻¹, 7000 s⁻¹ and 10,000 s⁻¹. The reduction in the sample size aims to obtain higher strain rates. Before tests, the sample is heated separately in a heater, i.e., a heating furnace. The sample temperature is monitored by a thermocouple. At the expected temperature, the sample is kept warm for a certain time, usually 3 min. Then the transmitted bar is pushed forward until the sample is fully in contact with the incident and transmission bars. In the test, the sample is sandwiched between the two loading bars as shown in Figure 2, and then the incident and transmitted bars are driven by a launching device of compression gas gun to impact the sample simultaneously. And lubricant MoS₂ is used to reduce the friction. According to the analysis on the incident, reflection and transmission waves, and the deformation of the sample is in consistence with the uniformity hypothesis on the stress distribution. All the tests are repeated at least three times. In the same way as mentioned in Section 2.2, the microstructure of the samples is analyzed.

![Figure 1. Optical microstructures of iron–nickel based ultra-high strength steel.](image)
3. Static and Dynamic Behavior

3.1. Static Behaviors vs. Strain Rate

The true stress–strain curves in Figure 3 are derived from the quasi-static compression tests at room temperature. The yield stress of iron–nickel based ultra-high strength steel is around 1800 MPa, and there is no obvious strain hardening or softening phenomenon. The strength is not sensitive to the strain rate in the quasi-static compression tests.

3.2. Dynamic Behaviors vs. Strain Rate

The effect of temperature on mechanical behaviors becomes complicated when it is coupled with strain rate. But in the SHPB tests, the strain rate hardening effect is witnessed. As shown in Figure 4, in both the low strain rate range from 500 s\(^{-1}\) to 2000 s\(^{-1}\) and the high strain rate range from 4000 s\(^{-1}\) to 10,000 s\(^{-1}\), the yield stress increases with the strain rate. While, when the wide range of strain rates from 500 s\(^{-1}\) to 10,000 s\(^{-1}\) is examined, the yield stresses in the low strain rate range are relatively higher than those in the high strain rate range. It is assumed that this is mainly caused by the
difference in the sample size. The sample size is reduced from $\Phi 4 \text{ mm} \times 4 \text{ mm}$ for low strain rate range to $\Phi 2 \text{ mm} \times 2 \text{ mm}$ for high strain rate range, so called size effect works [20–22].

Metallographic analysis shows that the microstructure of the samples has no obvious change and remains lath martensites. It indicates that at temperature 25 °C the deformation rate has no significant effect on the microstructure.

![Figure 4](image-url)  \textbf{Figure 4.} True stress–strain curves from SHPB tests at 25 °C.

In Figure 5a, the dynamic behavior at 300 °C shows similar variation tendency with respect to stain and stain rate as at 25 °C, except that at 300 °C a certain strain softening is presented at high strain rate of 7000 s$^{-1}$ and 10,000 s$^{-1}$. According to the optical photomicrographs in Figure 5b,c, the microstructures at strain rate of 7000 s$^{-1}$ and 10,000 s$^{-1}$ have no obvious change and remains tempered martensite. Therefore, strain softening is caused by the thermal-softening effect instead of phase transformation: In the SHPB compression process, most of the plastic deformation energy is transformed to heat. Because of the very low thermal conductivity induced by the high content of Ni, the heat dissipation to the environment takes a certain time. At high strain rate, more heat is retained in the sample and makes the temperature increase and the material soft. Thus, strain rate induced thermal-softening effect overcomes the strain-hardening effect.

![Figure 5a](image-url)
At 600 °C, both the rate-hardening and strain softening phenomena become more obvious as shown in Figure 6a. From Figure 6c–e, the density of lath martensitic grain boundary within the original austenite grain increases and the lath martensitic structure become narrowed. The dynamic recrystallization develops and grain refinement aggravates gradually with the strain rate increasing.

Dynamic recrystallization weakens the effect of work-hardening. Therefore, although at 600 °C the heat dissipation to the environment increases due to the increase of temperature difference between environment and sample and thermal-softening effect becomes weak, strain-softening phenomena are witnessed in Figure 6a and become more obvious with the strain rate increasing from 4000 s\(^{-1}\) to 10,000 s\(^{-1}\).
Figure 6. True stress–strain curves (a) and its corresponding optical photomicrographs of SHPB tested samples deformed at 600 °C with strain rate (b) 1000 s⁻¹; (c) 4000 s⁻¹; (d) 7000 s⁻¹ and (e) 10,000 s⁻¹.

According to Figure 7a, at 800 °C the material shows obvious steady strain-rate and strain hardening. And the grain boundaries from Figure 7b–e become more and more obscure with the increase of the strain rate. The grain boundaries are priority areas for solid state phase transformation due to the higher energy level where atoms arranged disorderedly and vacancies, dislocations and lattice distortions are centralized.
Figure 7. True stress–strain curves (a) and its corresponding optical photomicrographs of SHPB tested samples deformed at 800 °C with strain rate (b) 1000 s⁻¹; (c) 4000 s⁻¹; (d) 7000 s⁻¹ and (e) 10,000 s⁻¹.

At 1200 °C, the true stress-strain curves in Figure 8a show obvious steady strain-rate and strain hardening, which are similar to those in Figure 7a. But the microstructures becomes different, and reconstituted and deformed grains [23–27] with low-yield strength twin austenite is formed in Figure 8b–d.

Figure 8. (a) True stress–strain curves at 1200 °C; its corresponding optical photomicrographs of SHPB tested samples deformed at (b) 1000 s⁻¹; (c) 4000 s⁻¹ and (d) 7000 s⁻¹.

3.3. Dynamic Behaviors vs. Temperature

According to Figure 9, at a single strain rate, the stress–strain curve softened at 600 °C and hardened at 800 °C and above. Temperature has great effects on the dynamic behaviors of iron–nickel based ultra-high strength steel. Firstly, due to the thermal-softening effect, the flow stress decreases with the increase in temperature and improved material plasticity is demonstrated by the increased deformation at failure. Secondly, the varying tendency of the stress–strain curves from 300 °C to 800 °C shows that the dynamic behaviors experience change from strain-softening to strain-hardening.
But above 800 °C, the stress–strain curves show a similar tendency of slight strain-hardening. Thirdly, although the yield stress decreases with the increase in temperature, the yield strength shows different temperature sensitivity: combining with the Figures 6–8, a strong temperature sensitivity is witnessed around 600 °C because of dynamic recrystallization, while a weak temperature sensitivity at the deformation temperature much higher than 800 °C or lower than 300 °C.

**Figure 9.** Stress–strain curves of iron–nickel based ultra-high strength steel at different strain rates (a) 1000 s⁻¹; (b) 4000 s⁻¹; (c) 7000 s⁻¹; and (d) 10,000 s⁻¹.

### 3.4. Microhardness vs. Temperature and Strain Rate

The Wechsler microhardness is examined with a Tukon 2500 Vickers (Wilson, Chicago, IL, USA) microhardness tester at the Central Iron & Steel Research Institute. Each specimen is measured 5 times and takes the average. The standard deviation of the microhardness change is between 2.21 and 6.40. The original sample is 597 HV0.02. The microhardness of the sample is sensitive to the test temperature. With the increase of the SHPB test temperature, the microhardness of the sample decreases gradually. In Figure 10, the microhardness at 7000 s⁻¹ drops from 583 HV0.02 at 300 °C to 357 HV0.02 at 800 °C. At the same deformation temperature, the microhardness of the sample increases at the strain rate of 8000, and there is no obvious change at other strain rate.

According to the analysis on microhardness combined with the metallographic analysis in Section 3.2, the temperature around 600 °C may be a cut-off temperature point. Below 600 °C, the material is composed of large size tempered martensite grains with obvious grain boundary and the microhardness remains above 500 HV0.02. At 800 °C, although the metallurgical structures are still tempered martensite, the grain boundary become blurred and disappeared, and the Wechsler microhardness drops sharply to below 357 HV0.02. At 1200 °C, the metallurgical structures are twin austenite and the Wechsler microhardness drops to around 330 HV0.02.
4. Dynamic Recrystallization: Action Mechanism of Dynamic Behavior

In recent years, it is found that continuous dynamic recrystallization (CDRX) in the thermal deformation is not achieved by nucleation and growth of new grains like static recrystallization, but is formed by breaking the matrix grains, generating low angle grain boundaries by a large number of dislocations, gradually converting to high angle grain boundaries and forming the recrystallized grains [28–33]. Since the dynamic recrystallization process is realized directly through the movement of dislocation instead of nucleation of recrystallized grains, CDRX is able to proceed at a high speed.

The material mechanical behavior in hot deformation is decided by two mechanisms. On one hand, the increase in strain leads to the increase in strength, On the other hand, when the strain accumulation reaches a certain level, CDRX will take place and lead to the change of the microstructure, the reduction in the strength, and then cause the change of the macroscopic mechanical behavior.

4.1. Hot Deformation Equation

In plastic deformation, the deformation activation energy \( Q \) is an important physical quantity indicating the degree of deformation difficulty. The higher the deformation activation energy is, the larger the deformation energy barrier is, the more difficult the diffusion of metal atoms and the migration of grain boundaries will become, which is easily to lead to dynamic recrystallization.

In order to reveal the influence of temperature and strain rate on dynamic recrystallization, the Zener–Hollomon parameter is usually defined by Equation (1) [34].

\[
Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right)
\]  

(1)

where \( \dot{\varepsilon} \) is the strain rate (s\(^{-1}\)), \( Q \) is the activation energy (kJ·mol\(^{-1}\)), \( R \) is the thermodynamic parameter (8.314 mol/K), \( T \) is the temperature (K).

According to the studies from Ref. [35–37], the relationship between the flow stress and the strain rate at low stress can be described by the exponential function of Equation (2), and at high stress by the power exponential function of Equation (3). Equations (2) and (3) can be unified into Equation (4).

\[
\dot{\varepsilon} = f_1(\sigma) = A_1 \sigma^{n_1} \exp \left( -\frac{Q}{RT} \right)
\]  

(2)
where $\sigma$ is flow stress, $A_1, A_2, A_3, n_1, n_2, n_3$ are material-dependent coefficients, and $\alpha = \frac{n_2}{n_1}$ is a temperature-independent constant.

By taking the logarithm form of Equations (2)–(4), the relationship of peak stress to the strain rate is expressed as Equations (5)–(7).

$$\ln \dot{e} = \ln A_1 + n_1 \ln \sigma_p - \frac{Q}{RT}$$  
(5)

$$\ln \dot{e} = \ln A_2 + n_2 \sigma_p - \frac{Q}{RT}$$  
(6)

$$\ln \dot{e} = \ln A_3 + n_3 \ln[\sinh(\alpha \sigma_p)] - \frac{Q}{RT}$$  
(7)

The flow stress peaks $\sigma_p$ and strain rates at different temperatures are fitted linearly to get the lines of $\ln \dot{e} - \ln \sigma_p$, $\ln \dot{e} - \sigma_p$ and $\ln \dot{e} - \ln[\sinh(\alpha \sigma_p)]$ respectively. Based on the average slopes of these lines, the constants and coefficients are obtained as $n_1 = 11.50$, $n_2 = 0.024$, $\alpha = \frac{n_2}{n_1} = 0.0021$ and $n_3 = 7.48$. Then the Zener–Hollomon parameter is expressed as Equation (8).

$$Z = \dot{e} \exp \left( \frac{Q}{RT} \right) = A_3[\sinh(\alpha \sigma_p)]^{n_3}$$  
(8)

In Equation (7), as the strain rate keeps constant, $\ln(\sinh(\alpha \sigma_p))$ and $1/T$ are in linear relationship and can be written as Equation (9).

$$Q = R n_3 \frac{\partial \ln(\sinh(\alpha \sigma_p))}{\partial (1/T)} \dot{e}$$  
(9)

As a result, the dynamic recrystallization activation energy of 18Ni martensitic steel $Q = 206$ kJ/mol is defined by fitting the SHPB test data. Then the Zener–Hollomon parameter can be expressed as Equation (10).

$$Z = \dot{e} \exp \left( \frac{206 \times 10^3}{8.314T} \right)$$  
(10)

4.2. Critical Strain for Dynamic Recrystallization

Dynamic recrystallization occurs when the strain reaches a critical value $\epsilon_c$. The critical strain value varies with the temperature and strain rate and is related to $\epsilon_p$, i.e., $\epsilon_c = 0.83\epsilon_p$ [38,39].

$$\epsilon_p = kZ^n$$  
(11)

where $k$ and $n$ are coefficients. By fitting the experimental data, they are defined as $k = 9.07 \times 10^{-5}$ and $n = 0.2807$. Accordingly the critical strain is defined as Equation (12).

$$\epsilon_c = 9.07 \times 10^{-5}Z^{0.2807}$$  
(12)

Therefore, according to Figure 11, the critical strain value increases with increasing strain rate and has a cliff decrease at temperature 79.6°C and is not affected anymore above 79.6°C.
4.3. Microstructure Model

The volume fraction of the dynamic recrystallized grains $X_D$ can be calculated by Equation (13) [40]:

$$X_D = \frac{\sigma_{WH} - \sigma}{\sigma - \sigma_{SS}}, \varepsilon > \varepsilon_C$$  \hspace{1cm} (13)

where $\sigma_{WH}$ is instantaneous recovery flow stress (MPa); $\sigma_S$ is steady state recovery rheological stress (MPa); $\sigma$ is instantaneous dynamic recrystallization flow stress (MPa); $\sigma_{SS}$ is steady state dynamic recrystallization flow stress (MPa).

Based on Avrami dynamic recrystallization kinematics equation, the dynamic recrystallization fraction of 18Ni martensitic steel can be defined by Equation (14).

$$X_D = 1 - \exp[-k_d(\varepsilon - \varepsilon_C/\varepsilon_p)^{n_d}]$$  \hspace{1cm} (14)

where $k_d$ is the material constant and $n_d$ is the Avrami’s constant. Equation (15) is obtained by linear fitting Equation (14).

$$X_D = 1 - \exp \left[ -0.0834 \left( \frac{\varepsilon - \varepsilon_C}{\varepsilon_p} \right)^{1.4151} \right]$$  \hspace{1cm} (15)

Obviously, the rate of dynamic recrystallization $X_D$ increases with increasing strain rate. This is in consistent with the analysis on microstructure of the samples in mechanics deformation.

5. Conclusions

The mechanical and dynamic behaviors of iron–nickel based ultra-high strength steel in hot deformation are strongly correlated with strain, strain rate and temperature. In this paper, the relationship of stress to strain, strain rate, and temperature is systematically investigated by the dynamic compression tests combined with quasi-static compression tests, and the underlying mechanisms are discovered.

(1) Dynamic behavior of iron–nickel based ultra-high strength steel is a product of the combined actions of rate-hardening, thermal softening, and stain-hardening. The rate-hardening effect is witnessed at all deformation temperature, while stain-hardening is often synchronized with thermal softening and the dynamic behavior is a result of their competition and becomes much more complicated by the dynamic recrystallization.

(2) According to the analysis, the dynamic behavior at different deformation temperature is characterized by: equilibrium of thermal softening and strain hardening at 25 °C, thermal softening overcoming strain hardening at 300 °C, strain softening due to dynamic recrystallization at 600 °C, strain hardening with obscured grain boundaries at 800 °C, and strain hardening with formation of...
austenitic twins at 1200 °C. In the meanwhile, the microhardness always decreases with the increase in deformation temperature and increases with strain rate.

(3) According to the analysis on the stress-strain relationship, it is assumed that the dynamic recrystallization takes place around 600 °C. After the dynamic recrystallization activation energy of 18Ni martensitic steel $Q = 206.207 \text{ kJ/mol}$ is defined by fitting the SHPB test data, the expression equation of Zener–Hollomon parameter is obtained. Then the critical strain for dynamic recrystallization is deduced as $\varepsilon_c = 9.07 \times 10^{-5}Z^{0.2807}$ and the volume fraction of the dynamic recrystallized grains as $X_D = 1 - \exp\left[-0.0834\left(\frac{\varepsilon_c - \varepsilon_p}{\varepsilon_p}\right)^{1.4151}\right]$.

**Author Contributions:** Experiments performing, H.F., X.H., and L.X.; Analysis of experimental data, H.F., X.W., and L.X.; Model establishment and calculations, H.F., L.X., U.U., and A.U.R.; Paper writing and editing, H.F., U.U., M.H.A. and A.E.R. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China under Grant No. 51575051 and Deanship of Scientific Research at King Saud University grant number RG-1439-005.

**Acknowledgments:** The authors are grateful for the support from National Natural Science Foundation of China for funding through Grant No. 51575051 and extend their appreciation to the Deanship of Scientific Research at King Saud University for funding this work through research group number RG-1439-005.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**References**

1. Kitagawa, T.; Kubo, A.; Maekawa, K. Temperature and wear of cutting tools in high-speed machining of Inconel 718 and Ti 6Al 6V 2Sn. Wear 1997, 202, 142–148.
2. Abuklshim, N.A.; Mativenga, P.T.; Sheikh, M.A. Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining. Int. J. Mach. Tools Manuf. 2006, 46, 782–800.
3. Chakravarthi, K.V.A.; Koundinya, N.T.B.N.; Murty, S.N.; Rao, B.N. Microstructural Evolution and Constitutive Relationship of M350 Grade Maraging Steel during Hot Deformation. J. Mater. Eng. Perform. 2017, 26, 1174–1185.
4. Garrison, W.M. Ultrahigh-strength Steel for Aerospace Applications. J. Miner. 1990, 42, 20–24.
5. He, Y.; Yang, K.; Kong, F.; Qu, W.; Su, G. Mechanical Properties of Ultra-High-Strength 18Ni Cobalt-Free Maraging Steel. Acta Metall. Sin. 2002, 38, 278–282.
6. Yang, K.; Qu, W.S.; Kong, F.Y.; Su, G.Y. Effects of solution treatment temperature on grain growth and mechanical properties of high strength 18%Ni cobalt free maraging steel. Mater. Sci. Technol. 2003, 19, 117–124.
7. Sinha, P.P.; Tharian, K.T.; Sreekumar, K.; Nagarajan, K.V.; Sarma, D.S. Effect of aging on microstructure and mechanical properties of cobalt free 18%Ni (250 grade) maraging steel. Mater. Sci. Technol. 2013, 14, 1–9.
8. He, Y.; Yang, K.; Qu, W.; Kong, F.; Su, G. Study of Ultra-Purified 18Ni (350) Maraging Steel. Acta Metall. Sin. 2001, 37, 852–856.
9. Morito, S.; Kishida, I.; Maki, T. Microstructure of ausformed lath martensite in 18%Ni maraging steel. J. Phys. IV 2003, 112, 453–456.
10. Li, N.; Zhao, F.; Zhang, H.; Ren, Y.H. Kinetics of Dynamic Recrystallization of 18 Ni Maraging Steels. Mater. Sci. Forum 2016, 850, 13–20.
11. Zhao, F.; Ren, Y.H.; Yan, Y. Dynamic Recrystallization of 18Ni (1700MPa) Maraging Steel during Hot Deformation. Adv. Mater. Res. 2013, 602, 441–447.
12. Jeehani, S.; Ramakrishnan, K. Subsurface plastic deformation in machining annealed 18% Ni maraging steel. Wear 1982, 81, 263–273.
13. Zhao, H.; Gary, G. On the use of SHPB techniques to determine the dynamic behavior of materials in the range of small strains. Int. J. Solids Struct. 1996, 33, 3363–3375.
14. Yang, S.W.; Liu, L.M.; Wang, Y.W.; Ba, H.J. SHPB Experiment of Steel Fiber Reactive Powder Concrete Exposed to High Temperatur. J. Sichuan Univ. 2010, 42, 25–29.
15. Apostol, M.; Vuoristo, T.; Kuoikkala, V.T. High temperature high strain rate testing with a compressive SHPB. J. Phys. IV 2003, 110, 459–464.
16. Bin, M. Experimental and Simulation Research on Cutting Tool Wear for High Efficient Cutting of High-Strength Steel [D]; Beijing Institute of Technology: Beijing, China, 2014.

17. Kolsky, H. An Investigation of the Mechanical Properties of Materials at very High Rates of Loading. *Proc. Phys. Soc. 2002*, 62, 676.

18. Li, Y.L.; Suo, T.; Guo, W.G. High Temperature SHPB System with Heat Insulation for Short Ceramic Bars. *Exp. Shock Waves 2005*, 25, 487–492. (In Chinese)

19. Yin, Z.N.; Wang, T.J. Deformation of PC/ABS alloys at elevated temperatures and high strain rates. *Mater. Sci. Eng. A 2008*, 494, 304–313.

20. Wang, Q.Z.; Zhang, S.; Xie, H.P. Rock Dynamic Fracture Toughness Tested with Holed-Cracked Flattened Brazilian Discs Diametrically Impacted by SHPB and its Size Effect. *Exp. Mech. 2010*, 50, 877–885.

21. Rodriguez, J.; Cortés, R.; Martínez, M.A.; Sánchez-Gálvez, V.; Navarro, C. Numerical study of the specimen size effect in the split Hopkinson pressure bar tests. *J. Mater. Sci. 1995*, 30, 4720–4725.

22. Cao, D.F.; Liu, L.S.; Mei, H.; Zhang, Q.J. The Sensitivity of Strain Rate and Size Effect with Different Particle Volume Fraction in SiCp/Al Composite. *Mater. Sci. Forum 2009*, 631, 513–518.

23. Guo, Z.; Sha, W.; Li, D. Quantification of phase transformation kinetics of 18 wt% Ni C250 maraging steel. *Mater. Sci. Eng. A 2004*, 373, 10–20.

24. Ding, Z.; Li, B.; Liang, S.Y. Maraging steel phase transformation in high strain rate grinding. *Int. J. Adv. Manuf. Technol. 2015*, 80, 711–718.

25. Kapoor, R.; Kumar, L.; Batra, I.S. A dilatometric study of the continuous heating transformations in 18wt% Ni maraging steel of grade 350. *Mater. Sci. Eng. A 2003*, 352, 318–324.

26. Shin, S.Y.; Han, S.Y.; Hwang, B.; Lee, C.G.; Lee, S. Effects of Cu and B addition on microstructure and mechanical properties of high-strength bainitic steels. *Mater. Sci. Eng. A 2009*, 517, 212–218.

27. He, Z.; Ren, H. The phase transition temperature of the maraging alloys. *Mater. Mech. Eng. 1982*, 5, 23–26. (In Chinese)

28. Griffiths, B.J. Mechanisms of white layer generation with reference to machining and deformation processes. *J. Tribol. 1987*, 109, 525–530.

29. Ramesh, A.; Melkote, S.N. Modeling of white layer formation under thermally dominant conditions in orthogonal machining of hardened AISI 52100 steel. *Int. J. Mach. Tools Manuf. 2008*, 48, 402–414.

30. Schulze, V.; Uhmann, E.; Mahnken, R.; Menzel, A.; Biermann, D.; Zabel, A.; Bollig, P.; Ivanov, I.M.; Cheng, C.; Holtermann, R.; et al. Evaluation of different approaches for modeling phase transformations in machining simulation. *Prod. Eng. 2015*, 9, 437–449.

31. Darken, L.S.; Gurry, R.W. *Physical Chemistry of Metals*; CBS Press: New Delhi, India, 1953.

32. Müller, P.; Saül, A. Elastic effects on surface physics. *Surf. Sci. Rep. 2004*, 54, 157–258.

33. Fradkin, A.M. The effect of strain on the thermodynamics of the weakly first-order phase transition. *J. Phys. Condens. Matter 1997*, 9, 7925–7932.

34. Beynon, J.H.; Sellars, C.M. Modelling micro-structure and its effects during multipass hot rolling. *ISIJ Int. 1992*, 32, 359–367.

35. Sellars, C.M.; McTegart, W.J. On the mechanism of hot deformation. *Acta. Metall. 1966*, 14, 1136–1138.

36. Jonas, I.J.; Sellars, C.M.; Tegart, W.J.M. Strength and structure under hot-working conditions. *Metall. Rev. 1969*, 14, 1–24.

37. Ryan, N.D.; Mcqueen, H.J.; Evangelista, E. Dynamic recovery and strain hardening in the hot deformation of type 317 stainless steel. *Mater. Sci. Eng. A 1986*, 81, 259–272.

38. Glowacki, M.; Kuziak, R.; Malinowski, Z.; Pietrzyk, M. Modelling of heat transfer, plastic flow and microstructural evolution during shape rolling. *J. Mater. Proc. Technol. 1995*, 53, 159–166.

39. Kuziak, R.; Glowacki, M.; Pietrzyk, M. Modelling of plastic flow, heat transfer and microstructural evolution during rolling of eutectoid steel rods. *J. Mater. Proc. Technol. 1996*, 60, 589–596.

40. Sellars, C.M. Modelling microstructural development during hot rolling. *Mater. Sci. Technol. 1990*, 6, 1072–1081.