Shock response of stainless steel at high temperature

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Measurements of the dynamic tensile strength of HR-2 (Cr-Ni-Mn-N) stainless steel have been carried out over the initial temperature range of 300 K–1000 K at shock stress of 8 GPa, the corresponding spall strength σ_f and Hugoniot elastic limit σ_{HEL} are determined from the wave profiles. In the temperature range of 300 K–806 K, σ_f and σ_{HEL} decrease linearly with increasing temperature T, i.e., $\sigma_f = 5.63 - 4.32 \times 10^{-3} T$, $\sigma_{HEL} = 2.08 - 1.54 \times 10^{-3} T$, but when heated to 980 K, σ_{HEL} increases from 0.84 GPa at 806 K to 0.93 GPa at 980 K and σ_f keeps at an almost fixed value of 2.15 GPa. The TEM analysis on recovery samples identified the existence of intermatallic compound Ni_3Al and the carbide $Cr_{23}C_6$ in the sample of 806 K, another intermatallic compound Ni_3Ti was found in the sample of 980 K. All these products emerge along crystal boundary. While no such products were found in the samples of 300 K and 650 K.

1. Introduction
HR-2 stainless steel is one of the Austenitic stainless steel with nitrogen. Because of its high yield strength and excellent anticorrosion in a large range of temperatures, it has been used widely in areas of petrochemical industry, aerospace engineering and so on. Several studies on the dynamic behavior of this material at room temperature have been reported [1, 2]. Because this kind of steel would be used in the different environments, it is important to know the dynamic behavior of this material at different temperatures. On the other hand, this study will enlarge the use of this kind of steel. In this study, we report free surface velocity profiles measurement on HR-2 steel shock-compressed to about 8 GPa in the temperature range of 300 K–1000 K, and find that the spall strength of this steel does not decrease monotonically with temperature.

2. Experimental technique
Dynamic compression of the sample was carried out by high-velocity plate impact. 2-mm thickness of Armco iron flyer plate was mounted in lexan projectiles and accelerated to high velocity using a single-stage 100-mm bore light gas gun in Lab for Shock Wave and Detonation Physics Research, Southwest Institute of Fluid Physics. The projectile velocities were measured to ±1% by electrical shorting pins. The samples were cut from ϕ80 mm bar of HR-2 steel which had not been heat-treated before. Both the chemical composition and physical parameters of the sample were listed in Table I and II, the physical parameters of the armco iron was also listed in Table II.

We used a water-cooled copper induction coil powered by a 30-kW radio frequency generator to heat samples. The temperature of samples was measured to ±0.75% by a Ni90%Cr10%-Ni97%Si3% thermocouple, the whole heating process lasts 2–3 minutes. The motion of the free surface of the sample was recorded using a VISAR (velocity interferometer system for any reflected) of which the time resolution is ∼2–3 ns, the precision is ±1%.

The experimental set-up is indicated in Fig. 1. The sample was mounted on the target rings. The ceramic pipes and spacers were used to isolate the sample from other metal parts. Two electrical pins were arranged homogeneously on the sample, the pins were isolated from the targets with ceramic pipes and used as trigger of the oscilloscope (HP 54111D and Tek602A). The rear surface of the sample was lapped to finish for a better VISAR signal.

3. Experiment results
Six experiments were conducted on HR-2 steel samples at different initial temperature, four of which (300 K, 650 K, 806 K and 980 K respectively) yielded complete free surface velocity profiles, shown in Fig. 2. In the remaining two experiments (776 K and 896 K), some missing fringes prevented an elastic precursor from being obtained but the whole spall signals were recorded.

TABLE I Chemical composition of HR-2 steel. (values in weight percent)

C	Mn	Cr	Ni	Si	Ti	Al	N_2	S	P	Fe
0.037	8.95	20.53	7.64	0.41	0.1	0.85	0.29	0.007	0.012	62.0

TABLE II Physical constants of HR-2 steel and Armco iron

Material	Density (g/cm^3)	Melting point (°C)	Logitudial wave velocity (km/s)	Shear wave velocity (km/s)	Special heat (Cal/g °C)	Poisson's ratio
Fe	7.85	1512	5.96	3.24	0.115	0.28
HR-2	7.806	1410	5.747	3.158	0.115	0.28

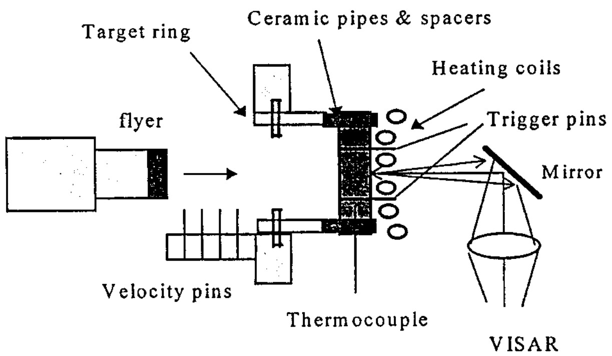

Figure 1 The Set-up for high-temperature VISAR experiments.

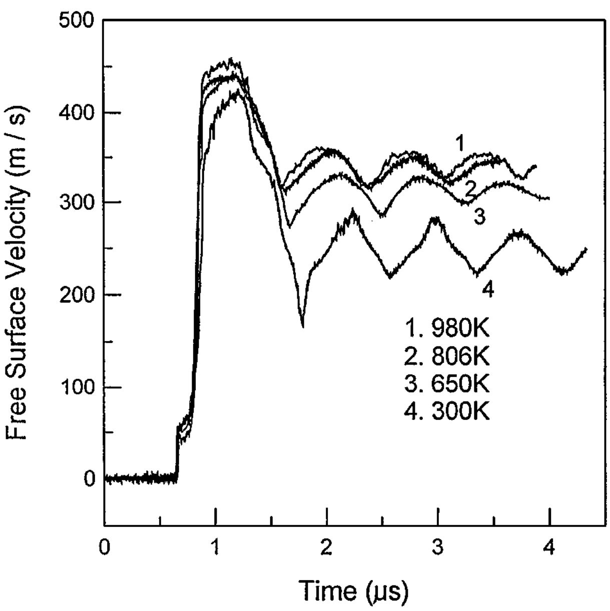

Figure 2 Free surface velocity of samples at different temperature (300 K, 650 K, 806 K, 980 K).

To establish timing for the experiments, the toes of the elastic precursor were assumed to propagate at the ambient-pressure, high temperature compressional wave velocity which was measured in ultrasonic experiments [3]. The time difference between the precursor and the midpoint of the shock established the shock velocity.

3.1. Spall strength

The spall strength, σ_f, is calculated from:

$$\sigma_f = \frac{1}{2}\rho_{0T} D \Delta u_{pb} \tag{1}$$

where D is shock velocity, obtained from experiments. Δu_{pb} is the pull-back amplitude measured from the peak free surface velocity to the velocity minimum. ρ_{0T} is the initial high-temperature density and in the form of:

$$\rho_{0T} = \rho_0(1 + 3\alpha T)^{-1} \tag{2}$$

ρ_0 is the initial room-temperature density, T is temperature, α is the linear expansion coefficient [4]:

$$\alpha(T) = 1.16422 \times 10^{-5} + 3.69496 \times 10^{-8} T - 3.98813 \times 10^{-11} T^2 \tag{3}$$

The spall strength data are given in Table III and are plotted as a function of initial temperature in Fig. 3 where the spall strength almost decreases linearly with temperature in the range of 300 K–806 K. A linear, least-square fitting to the data provides:

$$\sigma_f = 5.63 - 4.32 \times 10^{-3} T \tag{4}$$

while in the range of 806 K–980 K, the spall strength keeps at an almost fixed value of 2.15 GPa instead of decreasing with temperature.

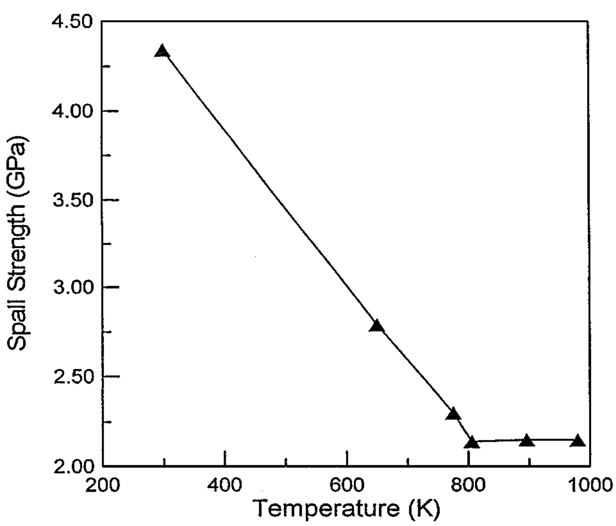

Figure 3 Spall strength of HR-2 steel as a function of initial temperature. (Solid line is a link line with the data.)

TABLE III Experimental results for HR-2 stainless steel at high temperature

Shot no.	Impact velocity (m/s)	Initial temperature (K)	Strain (10^{-2})	Strain ratio (10^6 s^{-1})	Hugoniot elastic limit (GPa)	Spall strength (GPa)	Yield strength (GPa)	Shock stress (GPa)
916	420	300	4.8	0.33	1.62	4.34	0.98	8.81
704	409	650	5.24	0.71	1.08	2.79	0.56	8.16
1027	426	776	—	—	—	2.30	—	—
628	410	806	5.24	0.76	0.84	2.14	0.41	7.86
107	400	896	—	—	—	2.15	—	—
702	411	980	5.46	0.465	0.93	2.15	0.44	7.58

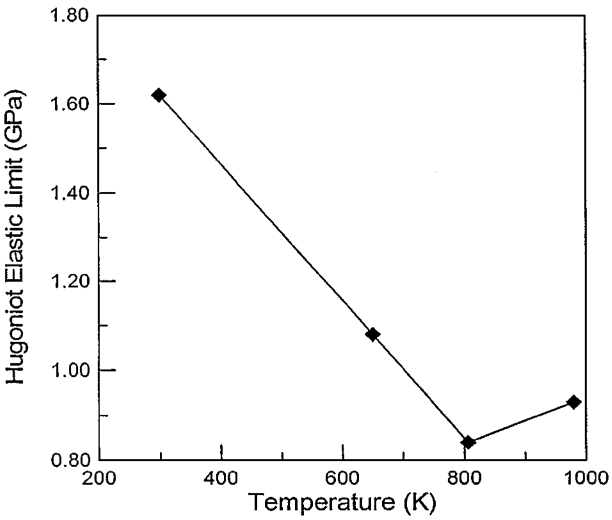

Figure 4 Hugoniot elastic limit as a function of initial temperature. (Solid line is a link line with the data.)

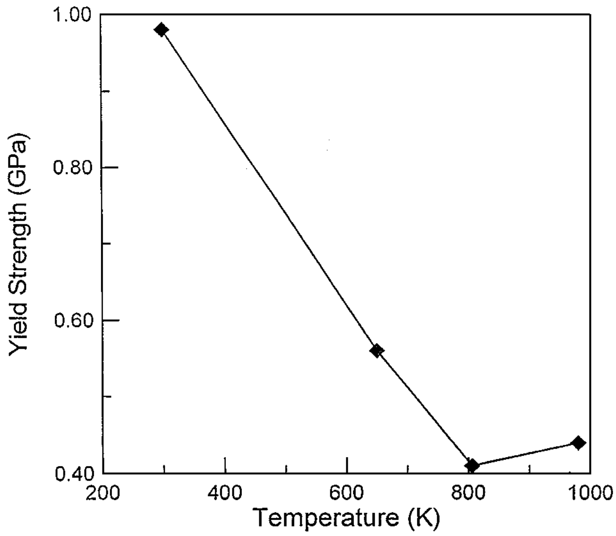

Figure 5 Yield strength as a function of initial temperature. (Solid line is a link line with the data.)

3.2. Hugoniot elastic limit

The Hugoniot elastic limit, σ_{HEL}, can be obtained from:

$$\sigma_{\mathrm{HEL}} = \frac{\rho_{0T} V_{\mathrm{p0}} u_{\mathrm{fs}}}{2} \tag{5}$$

where V_{p0} is the ambient-pressure, high-temperature compressional sound velocity [3], u_{fs} is free surface velocity corresponding to HEL (Hugoniot Elastic Limit). The factor-of-two relationship between the free surface and particle velocity has been used.

The σ_{HEL} datas are listed in Table III and are plotted as a function of initial temperature in Fig. 4. A linear, least-squares fitting to the data in the temperature range 300 K–806 K provides:

$$\sigma_{\mathrm{HEL}} = 2.08 - 1.54 \times 10^{-3} T \tag{6}$$

At 980 K, an unexpected large precursor was found, the HEL rises from 0.84 GPa at 806 K to 0.93 GPa.

3.3. Yield strength

Assuming a von Mises yield condition, the compressive yield strength, Y_0, is related to the HEL amplitude through:

$$Y_0 = \frac{(1-2\upsilon)}{(1-\upsilon)} \sigma_{\mathrm{HEL}} \tag{7}$$

where υ is Possion's ratio at different temperature, obtained from ultrasonic data of [3]. The resulting yield strengths are listed in Table III and plotted as a function of initial temperature in Fig. 5. A linear, least-squares fitting to the data in the temperature range 300 K–806 K provides:

$$Y_0 = 1.32 - 1.14 \times 10^{-3} T \tag{8}$$

The Hugoniot stress σ_{H} and strain ε_{f} were calculated in Table III according to the following expressions [5]:

$$\sigma_{\mathrm{H}} = \sigma_{\mathrm{HEL}} + \frac{\rho_{0T} D}{2}\left(U_{\mathrm{f}} - U_{\mathrm{fHEL}} + \frac{c_{\mathrm{l}} - c_0}{c_{\mathrm{l}} c_0} \cdot \frac{\sigma_{\mathrm{HEL}}}{\rho_{0T}}\right) \tag{9}$$

$$\varepsilon_{\mathrm{f}} = \frac{\sigma_{\mathrm{HEL}}}{\rho_{0T} c_{\mathrm{l}}^2} + \frac{\sigma_{\mathrm{f}} - \sigma_{\mathrm{HEL}}}{\rho_{0T} D^2} \tag{10}$$

where U_{f}, the peak free surface velocity; U_{fHEL}, HEL free surface velocity; c_0 and c_{l}, the bulk velocity and longitudial wave speed at different temperatures, respectively, were obtained from [3].

The maximum strain rate can be calculated and reported in Table III using the relation:

$$\varepsilon = \frac{1}{2D} \frac{\mathrm{d}U_{\mathrm{f}}}{\mathrm{d}t} \tag{11}$$

Where the time derivative is taken at the steepest part of the velocity profile.

4. TEM analysis on recovery sample

From the Figs 3–5, in the temperature range below and above 806 K, the dynamic behavior of the steel has an obvious change. Usually high temperature will lower the strength of metal, but in our experiments, the case is a little different. In order to explain the abnormal results, metallurgical analysis and TEM analysis were carried out on recovered samples of 300 K, 650 K, 806 K and 980 K. The raw materials were firstly identified as having an Austenitic structure with no other structure present. From the metallurgical analysis we can see clearly that the amount of slippage and deformation are increased with the rise of temperature under the same shock stress. From TEM analysis we can see no structures other than the Austenitic structure and some mechanical twin crystals were found in the recovered samples of 300 K and 650 K, shown in Fig. 6, which were produced by shock stress in the shock process. In the sample of 806 K, a new product was found which has a Face-Center-Cube (FCC) crystal structure, crystal constant A = 0.356 nm, and was identified as the intermetallic compound Ni_3Al, shown in Fig. 7. Another new product was also found which has the FCC structure and crystal constant A = 1.064 nm, and was identified as the carbide $Cr_{23}C_6$. In the sample of 980 K, another intermatallic compound Ni_3Ti was found which exists in two kinds of structure, one is a hexagonal pattern (H), A = 0.509 nm, C = 0.828 nm, shown in Fig. 8, which emerges as pellet sharp; the other is a Hexagonal-Close-Packed (HCP) structure, A = 0.511 nm, C = 0.831 nm, shown in Fig. 9, which appears as strip form. The difference in structure of Ni_3Ti maybe be caused by uneven shock stress and temperature distribution; the HCP structure is a stable state and the H structure is an unstable one. All the compounds are along the crystal boundary, the amount of product in sample 980 K were more than those in sample of 806 K. As we know, the intermatallic compounds have the character of higher strength at high temperature, so maybe the abnormal result at 980 K is due to the intermatallic compounds and carbide produced in the shock process.

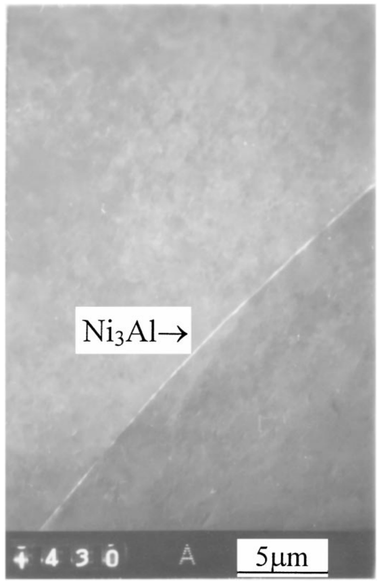

Figure 7 Photograph of Ni_3Al in the recovery sample of 806 K.

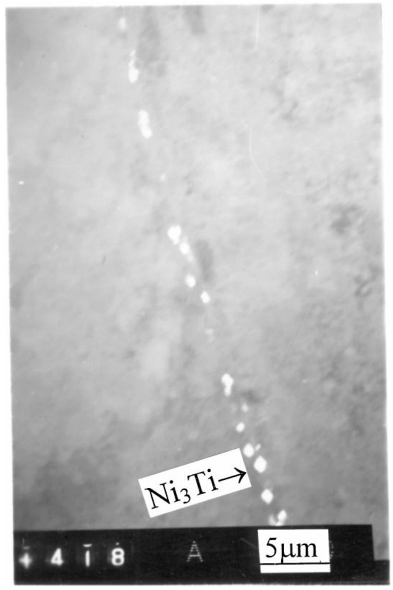

Figure 8 Photograph of Ni_3Ti with hexagonal pattern in the recovery sample of 980 K.

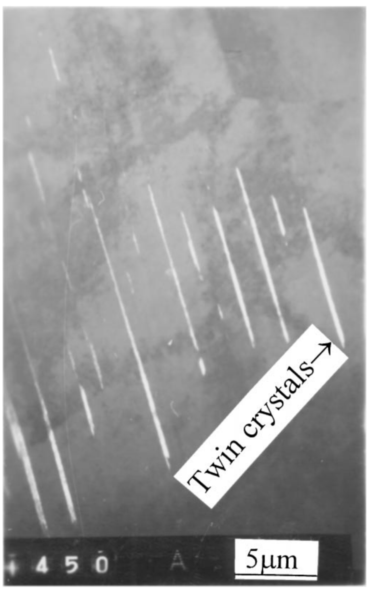

Figure 6 Photograph of mechanical twin crystals in the recovery sample of 650 K.

As we know, the rise of temperature will reinforce the strain ageing in steel. Now we don't know exactly the relationship between strain ageing and the produce of new compounds mentioned above, we will study it in the further research. W. Zhang [6] have done the spall experiment of the HR-2 steel at room temperature and shock stress of 12 GPa, the TEM analysis on recovery sample found nothing new. In the high temperature ultrasonic measurements on the HR-2 steel [3], in the range of 300 K–1400 K, the data is very linear. Because we have not done the experiments heating but without shocking, so we do not know exactly the changes in microstructure are due solely to the heating or result

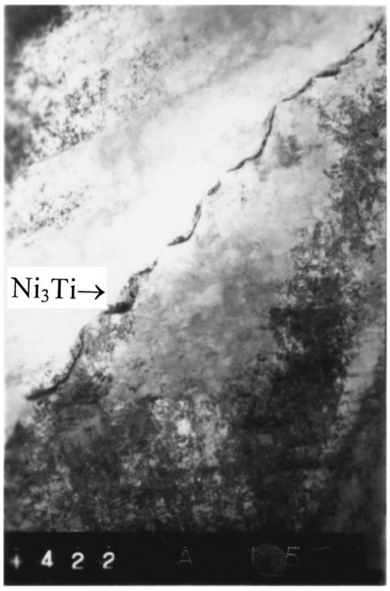

Figure 9 Photograph of Ni_3Ti with HCP structure in the recovery sample of 980 K.

from the thermal and shock processes, we are ready to conduct this experiment in the future.

5. Conclusion

Free surface velocities have been measured on HR-2 stainless steel preheated in the temperature range of 300 K–1000 K at shock stress of 8 GPa, the following results are obtained:

(1) In the range of 300–806 K, spall strength σ_f, Hugoniot Elastic Limit σ_{HEL} and yield strength Y_0 decrease linearly with increasing temperature T, and can be expressed: $\sigma_f = 5.63 - 4.32 \times 10^{-3}T$; $\sigma_{HEL} = 2.08 - 1.54 \times 10^{-3}T$; $Y_0 = 1.32 - 1.14 \times 10^{-3}T$. While in the range of 806 K–980 K, both σ_{HEL} and Y_0 have a little increase, σ_f keeps at an almost fixed value.

(2) The TEM test on recovery samples identified the existence of intermatallic compound Ni_3Al and the carbide $Cr_{23}C_6$ in the recovery sample of 806 K; another intermatallic compound Ni_3Ti was found in the sample of 980 K which has two kinds of structure, "H" pattern and "HCP" pattern. All these compounds are emerged along crystal boundary.

(3) According to the TEM analysis on the recovery samples, because the intermatallic compounds have the character of higher strength at high temperature, and additionally because the carbide $Cr_{23}C_6$ also has higher strength than that of the steel, so the experiment results at 980 K are probably due to these intermatallic compounds and carbide formations.

Acknowledgements

The authors would like to thank Prof. Qingfu Zhang and Yue Sun for their help in Experimental installations. The following colleagues who took part in the experiments are also thanked: Hongliang He, Wei Wang, Xiaosong Wang, Xiang Wang, and Quiwei Fu. This work performed under auspices of Science foundation of China Academy of Engineering Physics.

References

1. SHIHUI HUANG and XIAOGANG JIN, in Proceedings of the Conference on Shock Waves in Condensed Matter, 1994, p. 1083.
2. J. L. WISE and D. E. MIKKOLA, in Proceedings of the Conference on Shock Waves in Condensed Matter, 1988, p. 261.
3. HANZHAO ZHANG, Ultrasonic measurements of the dense and porous materials, CAEP Report, unpublished.
4. SHIJING LU, "Stainless Steel" (Atomic Energy Press, Beijing, 1995) p. 173 (in Chinese).
5. D. E. GRADY, in "Metallurgical Applications of Shock-Wave and High Strain Rate Phenomena," edited by L. E. Murr, K. P. Staudhammer and M. A. Meyers (Marcel Dekker, New York, 1986) p. 763.
6. W. ZHANG, Macroscopic and microcosmic research on the dynamic response of the anti-hydrogen steel under high strain rate, CAEP Report, GW0096G01, unpublished.

Received 22 January 1998
and accepted 25 August 1999