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Experimental Study on Phase Transition and Spall Fracture in FeMnNi Alloy under Shock Pressure*

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Abstract: By means of velocity interferometer system for any reflector (VISAR), X-ray diffraction (XRD) and scanning electron microscope (SEM), phase transition and spalling behavior of the FeMnNi alloy were studied through symmetric impact and reverse impact experiments. The FeMnNi alloy experiences a $\alpha \rightarrow \varepsilon$ phase transformation when shocked to the pressure above 6.5 GPa. The FeMnNi alloy produces $\varepsilon \rightarrow \alpha$ reverse phase transition and rarefaction shock wave when the pressure reduce to 4～5 GPa due to the rarefaction wave. By analyzing the interaction among plastic wave, phase transition wave, rarefaction wave and rarefaction shock wave, it was found that the FeMnNi alloy has a physical mechanism inducing the formation of spall behavior in symmetric impact experiments as the impact stress exceeds $\alpha \rightarrow \varepsilon$ transition threshold.

Key words: FeMnNi alloy; phase transition; reverse transition; spall; rarefaction shock wave

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1 Introduction

The spalling study is a wide field of interest. When a material is subjected to polymorphic phase transition under shock, the wave structure is extremly complex, and there is the possibility of rarefaction shock wave (RSW) formation, which may affect the damage behavior[1-7].

In this paper we are interested in the relationship between spall and phase transition behavior. The influences of phase transition on the spalling response for FeMnNi alloy are investigated by means of symmetric and same thickness impact and reverse impact experiments. The FeMnNi alloy with the single α phase, whose nominal composition (mass fraction) is Fe 85.03%, Mn 7.63%, Ni 7.01% and Al 0.30%, was selected in this study[8-9]. The symmetric impact experiment was to study the spalling behavior and the shock wave structure of FeMnNi alloy undergoing $\alpha \rightarrow \varepsilon$ phase transition. The reverse impact experiment was to reasearch the reverse phase transition and the rarefaction shock wave of the FeMnNi alloy.

2 Experimental Setup and Measuring Technique

The shock experiments were conducted on a 100 mm single stage light gas gun. Our principal

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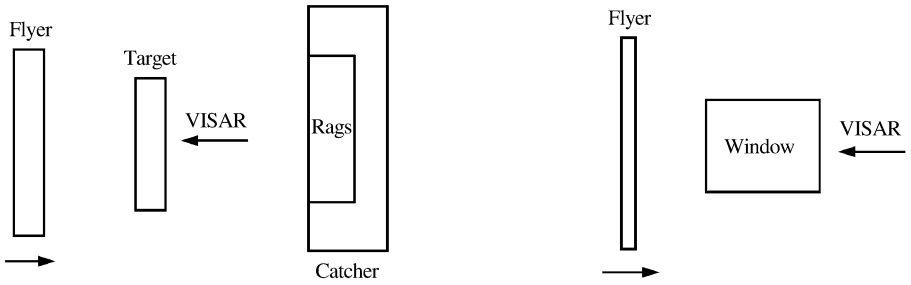
diagnostic is a double-sensitivity velocity interferometer system for any reflector (VISAR)(100 m/s and 250 m/s). The symmetric and same thickness impact and reverse impact experiments were carried out as shown in Fig. 1. The symmetric impact experimental set up is shown in Fig. 1(a), where the FeMnNi target plate and the FeMnNi flyer plate are the same thickness. The surface velocity of the sample opposite were measured by VISAR, and a catcher was used to recover the sample. Fig. 1(b) shows the reverse impact configuration which comprises of a FeMnNi flyer plate, a sapphire window and a VISAR measurement of the flyer/window interface velocity. The parameters of experimental conditions are listed in Table 1.



(a) Symmetric and same thickness impact (b) Reverse impact

Fig. 1 Schematic of the experimental setup

Table 1 Parameters of experimental conditions

Experiment number	Pressure /(GPa)	Size of FeMnNi flyer /(mm×mm)	Size of sapphire window /(mm×mm)	Size of FeMnNi target /(mm×mm)
1#	12.2	∅95×6.0		∅95×6.0
2#	11.9	∅95×2.0	∅45×15.0	

3 Experimental Results and Discussion

3.1 Symmetric and Same Thickness Impact Experiment

In symmetric impact experiment, when the impact pressure is higher than $\alpha \rightarrow \varepsilon$ phase transition pressure, FeMnNi alloy phase transition takes place both in impactor and target. The shock wave separates into three distinct waves while progressing through the target, and the VISAR detects them when they arrive at the free surface and accelerate it. The velocity of the target free surface as a function of time in experiment 1# is shown in Fig. 2. The first wave to appear is an elastic wave E; it is a sensitive indication of the sample quality. Next is a plastic wave P1, which takes the target up to a pressure no higher than that at which the $\alpha \rightarrow \varepsilon$ phase transformation begins. The third wave P2 occurs only when the shock pressure is sufficient to cause the phase transformation. Because the phase transformation occurs gradually, P2 rises slowly as the material transforms. The transition pressure of this FeMnNi alloy (6.5 GPa) can be obtained from the velocity of the target free surface (Fig. 2). And no spalling happens in the target from the target free surface velocity.

In the symmetric and same thickness impact experiment, we have recovered the target. The recovered target also indicates that no spalling happens in the target. It is according with the result of the target free surface velocity.

In order to obtain more information about the phase transition and spalling behavior, we studied the microcosmic configuration of the recovered target by means of X-ray diffraction (XRD) and scan electron microscopy (SEM).

The results of XRD is shown in Fig. 3. It illustrates the original FeMnNi alloy sample is α-phase. After undergoing loading and unloading, the FeMnNi alloy sample is also α-phase, no ε-phase is found. The result indicates that the FeMnNi alloy experiences a $\alpha \rightarrow \varepsilon$ phase transformation during the shock impact process and then experiences an $\varepsilon \rightarrow \alpha$ reverse phase transformation during the rarefaction.

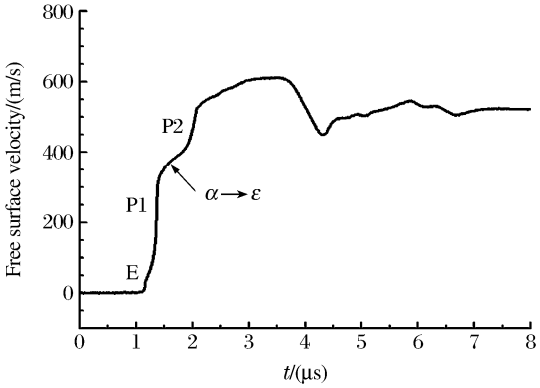


Fig. 2　Free surface velocity profile in experiment 1#

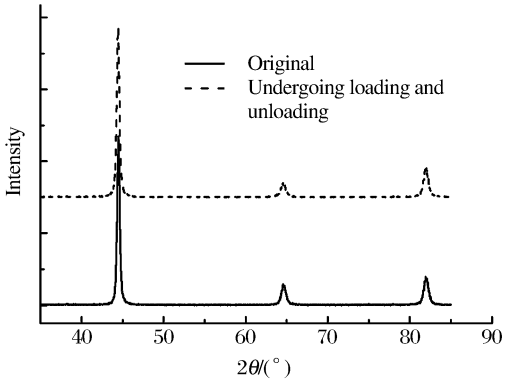
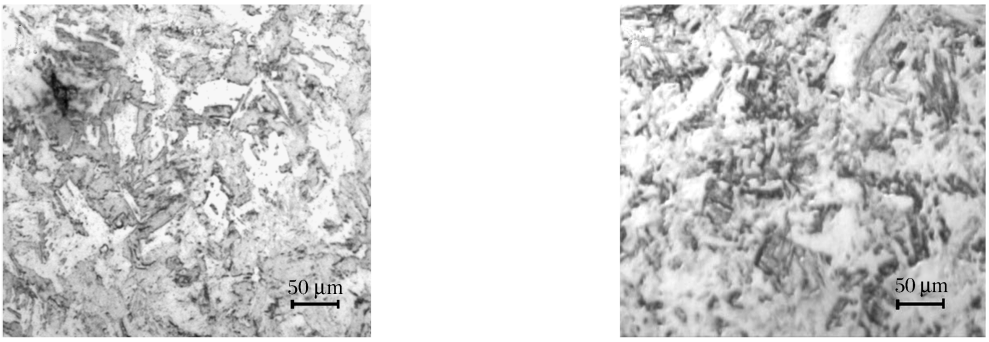


Fig. 3　XRD patterns of the FeMnNi alloy

Fig. 4 shows the result of SEM. From the picture, we can see that the original metallographic configuration of the FeMnNi alloy sample is α-phase. Just like the result of XRD, the microstructure of the FeMnNi alloy sample undergoing loading and unloading also is α-phase, no ε-phase is found. Consequently, it also demonstrates that the FeMnNi alloy target produces $\alpha \rightarrow \varepsilon$ phase transition during the impact process, the ε-phase is unsteady, and then the sample produces an $\varepsilon \rightarrow \alpha$ reverse phase transition during the rarefaction.



(a) Original　　(b) Undergoing loading and unloading

Fig. 4　SEM micrographs of the FeMnNi alloy

3.2　Reverse Impact Experiment

To observe the characteristic of the reverse phase transformation and the RSW in the FeMnNi alloy sample, we designed a reverse impact experiment 2# as shown in Fig. 1(b). The impedance (sound speed times density) of the sapphire is nearly that of FeMnNi alloy, minimizing reflections at the interfaces. The 15 mm thick sapphire window ensures no rarefaction wave reflecting from the rear surface. The shock pressure used in this test is about 12 GPa which is much higher than that of the phase transition (6.5 GPa) for this alloy, leading to occurrence of the $\alpha \rightarrow \varepsilon$ phase transition in the flyer, and forming a multi-wave structure which consists of an elastic wave E, a plastic wave P1 and a phase transition wave P2. But the multiwaves do not split at the impact surface, and they will be registered by VISAR as a single signal. These waves travel to the back free surface of the FeMnNi flyer. Because the magnitude of the elastic wave is so small that it can be neglected in the wave analysis.

The plastic wave P1 reflects at the rear side of the flyer and travels as a rarefaction wave back into the flyer, and then the rarefaction wave collides with the oncoming phase wave P2. When the leading edge of the rarefaction wave from the flyer arrives, the interface velocity begins to slow. We have observed the first rarefaction wave R by using VISAR technique. The phase wave P2, which has collided with the rarefaction wave R, interacts with the boundary and travels back as the second rarefaction wave into the flyer. The second rarefaction wave causes the interface velocity to suddenly drop, so we presumed that the second rarefaction wave is a RSW induced by the $\varepsilon \rightarrow \alpha$ reverse phase transition. The FeMnNi/sapphire interface velocity is shown in Fig. 5. From the picture, two points can be outlined.

(1) The first rarefaction wave R1 generated by the reflection of the plastic wave leads the $\varepsilon \rightarrow \alpha$ reverse phase transition to begin, but it is not complete, the high pressure α-phase transforms to a metastable mixed phase. Because the wave velocity of the metastable phase is lower than that of high pressure ε-phase, the time difference from wave front to wave tail of the rarefaction wave R increase, and no rarefaction shock wave occurs. The second rarefaction wave caused by the reflection of the oncoming phase wave leads the $\varepsilon \rightarrow \alpha$ reverse phase transition to entirely complete, and then the RSW forms.

(2) The phase transition pressures are about 6.5 GPa for $\alpha \rightarrow \varepsilon$ and about 4～5 GPa for $\varepsilon \rightarrow \alpha$ in FeMnNi alloy. The forward-reverse transition decay pressure is about 2～3 GPa. The FeMnNi alloy holds the typical hysteresis characteristic of martensite phase transition.

3.3 Discussion

For the experiment of 1#, the interaction process among the shock wave, the rarefaction wave R and the RSW in the target is shown in Fig. 6. The wave structures in the flyer and in the target are symmetric along the impact surface. Because the magnitude of the elastic wave E is very small, it could be neglected in the wave interaction process analysis. The plastic shock wave P1 interacts with the boundary and travels back into the target as a rarefaction wave R. The R collides with the oncoming phase transition wave P2, then travels back into ε-phase and lowers the pressure, and ε-phase is transformed into a metastable phase, the time difference from wave front to wave tail of the rarefaction wave R augments. The rarefaction wave R collides with the reflecting rarefaction wave at the rear surface of the flyer plate, and the first tension region comes into being. The phase wave P2, which has collided with the rarefaction wave R, reflects at the target free surface, and it travels back into the target as a rarefaction wave and cuts down the pressure of the target. After that, the metastable phase is entirely transformed into α-phase, and the RSW forms. The interaction between RSW and the residue of the right rarefaction wave R through the first tension region induces the second tension region. The tension stress is likely less than the spall strength, and no spalling happens in symmetric and thickness impact experiment (Experiment 1#).

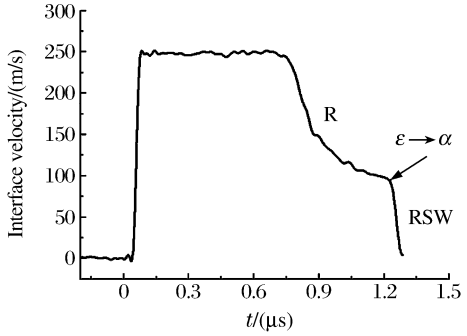


Fig. 5 Release velocity profile of the FeMnNi alloy

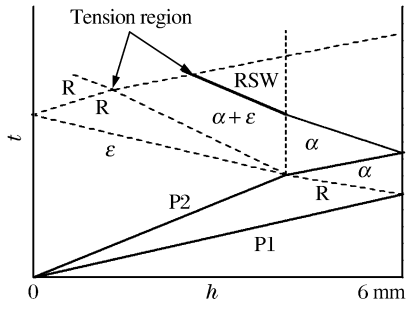


Fig. 6 Schematic diagram of stress wave interaction

4 Conclusions

When the shock pressure beyond 6.5 GPa, the FeMnNi alloy experiences a $\alpha \rightarrow \varepsilon$ phase transformation. As the rarefaction wave reduces the pressure of the sample near to 4～5 GPa, the FeMnNi alloy sample produces an $\varepsilon \rightarrow \alpha$ reverse phase transformation and the rarefaction shock wave. The forward-reverse transition decay pressure is about 2～3 GPa. The FeMnNi alloy holds the typical hysteresis characteristic of martensite phase transition.

The FeMnNi alloy sample has the physical mechanism of spalling behavior in symmetric and same thickness impact experiment, when shocked to above $\alpha \rightarrow \varepsilon$ transition threshold. And the spalling phenomena are believed to relate to the $\alpha \rightarrow \varepsilon$ phase transition, the $\varepsilon \rightarrow \alpha$ reverse phase transformation and the rarefaction shock wave.

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冲击加载下 FeMnNi 合金相变和层裂特性实验研究

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摘要:采用激光速度干涉仪(VISAR)、X 射线衍射(XRD)和扫描电镜(SEM)联合测试技术,利用等厚对称加载和逆向加载实验,研究了 FeMnNi 合金的冲击相变和层裂行为。结果发现:加载压力大于 6.5 GPa 时,FeMnNi 合金样品发生 $\alpha \rightarrow \varepsilon$ 相变;中心稀疏波的卸载作用使内压力降至 4～5 GPa 时,FeMnNi 合金样品发生 $\varepsilon \rightarrow \alpha$ 逆相变,并伴有卸载稀疏冲击波形成。分析 FeMnNi 合金样品中塑性波、相变波、稀疏波和稀疏冲击波的传播作用过程,发现加载压力大于其相变应力时,等厚对称加载下 FeMnNi 合金存在产生层裂行为的物理机制。

关键词:FeMnNi 合金;相变;逆相变;层裂;稀疏冲击波

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