Tension fracture behaviors of welded joints in X70 steel pipeline

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Abstract The surface of welded joints in X70 steel pipeline was processed by laser shock wave, its mechanical behaviors of tension fracture were analyzed with tension test, and the fracture morphologies and the distributions of chemical element were observed with scanning electron microscope and energy dispersive spectrum, respectively. The experimental results show that the phenomenon of grain refinement occurs in the surface of welded joints in X70 steel pipeline after the laser shock processing, and compressive residual stress is formed in its surface strengthened layer. There is no yield stage but a continuous yield behavior in the welded joints in X70 steel pipeline after the laser shock processing, and its extensibility has decreased by 20 %. The welded joints in X70 steel pipeline in primitive state exhibits brittle fracture with less tearing edges, while the fracture of welded joints in X70 steel pipeline processed by laser shock is ductile fracture with a lot of tearing edges. [doi:10.1063/2.1103108]

Keywords laser shock processing, welded joint, tension property, fracture morphology

With increasing demands from petroleum and natural gas industries, X70 pipeline steel is widely used as the transportation pipeline of petroleum and natural gas, and then high strength and tenacity welded pipe is produced by plate forming and welding.[1] Coarse crystal grains are formed and residual stress emerges during the welding process, which will reduce its mechanical properties, e.g. the intensity of welded joint in X70 steel pipeline is generally 50%–60% of that of the substrate, and its mechanical properties are also less than that of the substrate, making it the weakest linkage.[2] At present, the main strengthening method for improving the performance of welded joint is heat treatment or strain hardening, such as shot blast, ultrasonic wave, detonation, roller compaction, hammer performance and etc.[3,4] Laser shock processing uses the stress wave produced by strong pulse laser wave to generate plastic strain on the surface layer and thus affect the material tensile mechanical properties. It improves the geometrical shape of welded joint, eliminates the defects of the welded joint surface, produces compressive residual stress and enhances its tensile strength.[5] In this paper, the microstructures, the tensile fracture morphologies and inclusions of welded joints in X70 steel pipeline at normal temperature were observed via microscope, microscopic analysis, spectrum micro-area analysis, respectively, the reasons of tensile fracture occurrence were discussed, and the mechanism underlying strengthening phenomenon was also investigated.

The experimental material was rolled sheet of X70 pipeline steel, and the welding process was submerged arc automatic welding, inside and outside welding. The gauge length of the specimen was 25 mm, and its internal diameter was 3 mm, the clamp part was M8 thread of 15 mm length, as shown in Fig. 1. The welded joint was located at the middle of experimental material, and its chemical composition were shown as follows: C 0.07%, Si 0.22%, Mn 1.18% and the rest was Fe. Laser shock wave was applied to strengthen the welded joints, the coating was aluminum foil of 0.1 mm thickness, the restraint level was water of 2 mm thickness and the joining rate was 50%. The technological parameters were: pulse width 22 ns, wave length 1.054 μm, enlargement original radiation pulse width 1 μs and focusing focal diameter 3 mm. The tension test was carried on with the SERT-5000-D9H type slow strain speed testing machine, the load strain speed was 10^{-5} s^{-1}, and a displacement extensometer was set up within the specimen gauge to measure the distortion in the scale distance. In the process of experiment, the stretch load-displacement curve of the X70 pipeline steel test specimen was obtained by a computer data acquisition system, and the load-displacement curves were converted into the stress-strain curve.

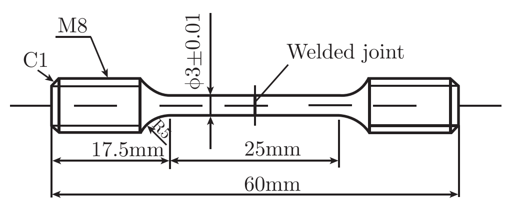

Fig. 1. Sketch of the sample.

The microstructures of weld joint in X70 steel pipeline after submerged arc automatic welding were shown in Fig. 2 (a), where the crystal grain in the welded zone was quite big. The grain refinement in the surface layer after the laser shock processing was shown in Fig. 2 (b). Larger plastic deformation occurred on the surface of X70 pipeline steel under the strong laser, and the impact energy produced by laser shock wave was mostly transformed

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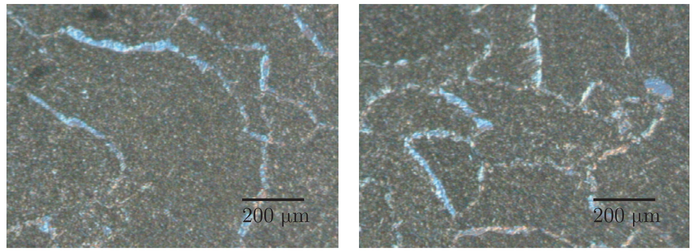
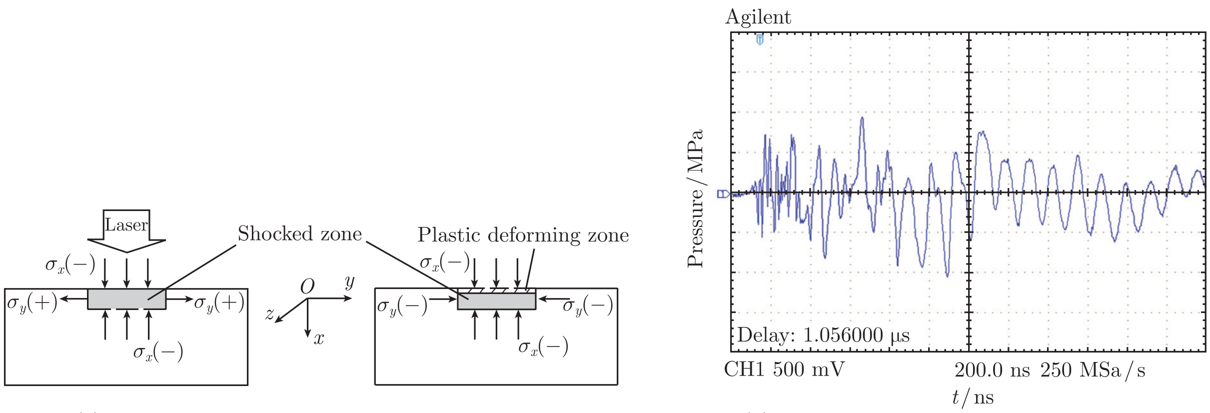


(a) In primitive state (b) After laser shock processing

Fig. 2. Metallurgical structures of welded joints in X70 steel pipeline



(a) Sketch of compressive residual stress production (b) The type of stress wave by laser shock wave

Fig. 3. The formation process of compressive residual stress

into plastic energy with little consumed in elastic energy. The surface structures of welded joint in X70 steel pipeline exhibited obvious refined phenomenon, and the dislocation density had increased.[6] The metal surface layer withstood impact had undergone intense plastic deformation process, causing the dislocations slipping and multiplied massively, which led to a sharp growth in the internal dislocation density. The micro-plastic deformation recovery was not completed during the laser shock processing. According to the grain refinement of plastic deformation dislocation theory, the surface micro-hardness of the sample after the laser shock processing had increased from 220–235 HV to 250–265 HV, and a strengthened layer was formed in the surface of welded joint, so that the hardness of the welded zone, fusion zone and heat-affected zone had risen markedly, which would help improve mechanical properties of the welded joint.

The elastic deformation was not restored completely after the laser shock processing, and thus residual stress was generated,[7] as showed in Fig. 3 (a). The shock-wave pressure produced by the laser shock processing weakened very quickly in the level direction. The mode of stress wave was measured with the ST27-CS4135A type oscilloscope (Fig. 3 (b)), and the attenuation range depended on the material density and mechanical properties. In the process of laser and material interaction, the shock wave produced tensile stress parallel to the material surface in the shocked zone, and then plastic deformation occurred. When the laser was turned off, because of the existence of plastic zone and the reaction around the shocked zone, compressive residual stress took place, which eliminated the welding superficial tensile stress and helped increase its tensile strength. Residual stress in the surface had impacts on the material strength. Residual stress played the same role as average stress in response to loading. Compressive residual stress was somewhat equivalent to negative average stress, and thus enhanced its strength. Tensile residual stress was equivalent to positive average stress, and thus decreased its strength.[7] The results of residual stress showed that the values of residual stress generated by the laser shock processing were changed into -297.6 ± 11.6 MPa compressive stress from 329.5 ± 30.0 MPa tensile stress in primitive state. The measured results of residual stress were given in Table 1.

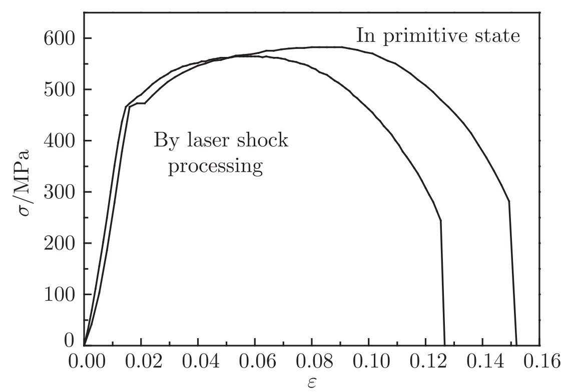
Figure 4 (a) showed the stress-strain curve of welded joint tensile specimen, which contained the following three zones: elastic deforming linear zone, plastic deforming non-line zone and transition zone. In later period of each curve, it was displayed that the strain increased while the stress dropped, which indicated there was a necking phenomenon when stretched. The analysis results of tension test were listed in Table 2. The welded joints in X70 steel pipeline in primitive state had a lower elongation rate of continuous yield and had obvious yield platform, and there appeared an apparent necking before breakage (Fig. 4 (b)), which was expressed in the form of a larger brittle fracture. The

Table 1. The measured results of residual stress

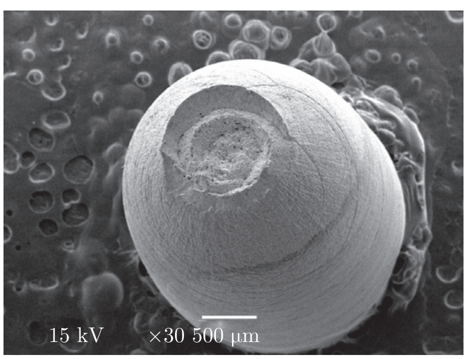
Residual stress σ/MPa	329.5±30.0				−297.6±11.6			
$\Psi/(^\circ)$	0.0	15.0	25.0	35.0	0.0	15.0	25.0	35.0
$2\theta/(^\circ)$	110.807	110.967	110.795	110.786	110.757	110.720	110.842	110.851
The counts of peak values	731	499	410	329	344	313	293	251
The width of Half height$\beta/(^\circ)$	1.62	1.59	2.03	2.03	2.41	2.68	2.72	2.50
Integral strength	681	766	663	617	834	825	581	662
Integral width/$(^\circ)$	1.58	1.54	1.62	1.88	2.42	2.64	1.98	2.64

Table 2. The tension test results of welded joints in X70 steel pipeline

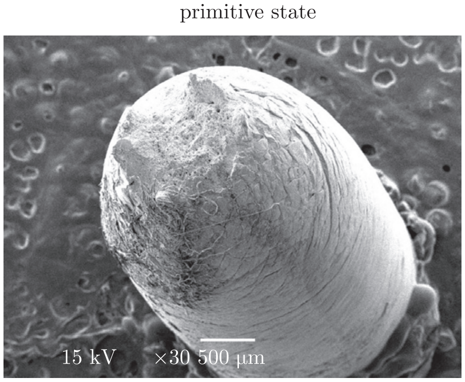
Mechanical properties	Strain rate/ (10^{-5}s^{-1})	Yield strength/ MPa	Tensile strength/ MPa	Elongation rate/%	Inner power
In primitive state	0.5	490	603.6	15.2	260
By laser shock processing	0.5	485.3	587.8	12.67	210



(a) The stress-strain curve



(b) The necking of the sample in primitive state

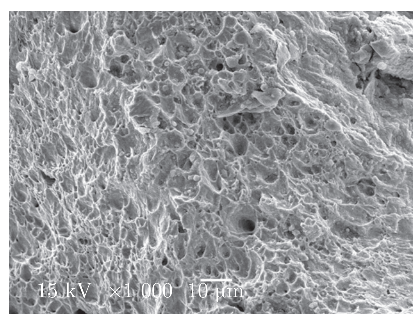


(c) The necking of the sample after laser shock processing

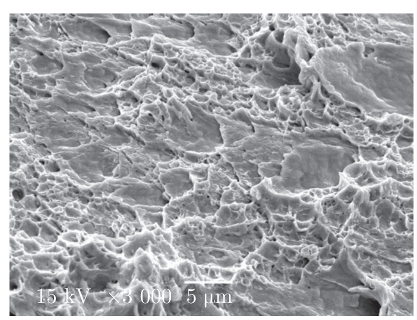
Fig. 4. The tensile curve of stress-strain

welded joints under the load of laser shock processing had a stronger deformation resistance, and had neither obvious platform nor apparent necking, as showed in Fig. 4 (c). It could be seen that the elongation rate of welded joint in X70 steel pipeline had decreased by 20 % while its strength and fracture toughness had increased, which benefits the improvement of its fracture performers.

The microscopic fracture of welded joint in X70 steel pipeline after tension test was of tough fracture type with strong nest and the tearing edge, as showed in Fig. 5 (a). The initial state fracture was of big piece river pattern, accompanied with few tearing edge, showing that the material plasticity was bad, simultaneously, the micro-cavity could easily be seen on the fracture, which might be caused by the welding residual gas that

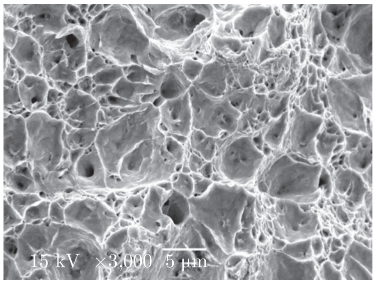


(a) In primitive state

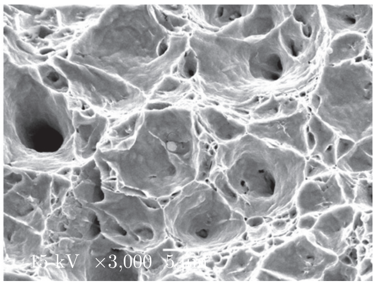


(b) After laser shock processing

Fig. 5. The fracture modes of welded joints

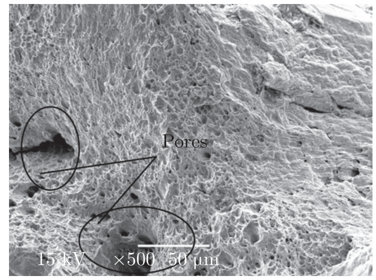


(a) In primitive

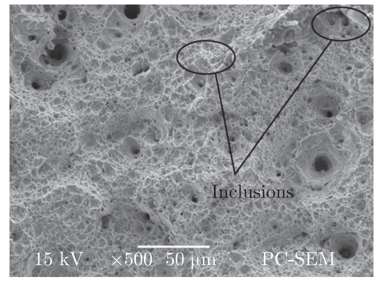


(b) After laser shock processing

Fig. 6. The dimple shapes of the welded joint fractures



(a) The small pores



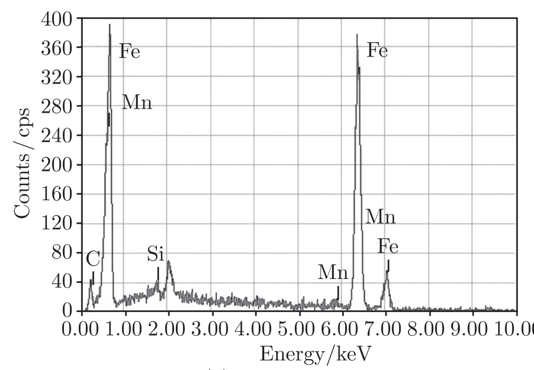
(b) The blocky inclusions

Fig. 7. The welding defects of the fracture in welded joints in X70 steel pipeline

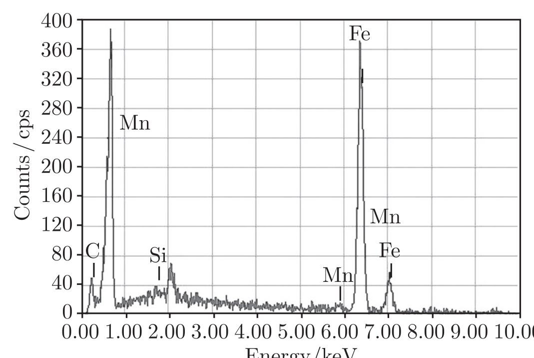
had not been excluded.[8] After the laser shock processing, the fracture exhbited big piece river pattern, accompanied with massive tearing edges (Fig. 5 (b)), where plastic fracture was obvious.

It could be seen from Fig. 8 that the tensile fracture exhibited smaller strong dimple before the laser shock processing. The initial state fracture exhibited quite densely distributed small strong dimple, as showed in Fig. 6 (a). There appeared great size and deep strong dimple in the fracture after the laser shock processing (Fig. 6 (b)). The stronger the nest size, the better the material toughness.[9]

The occurrence of tensile failure after the laser shock processing was caused by welding defects, which was reflected in two aspects: (1) the welded joint had circular or similar small pores (Fig. 7 (a)); (2) the weld joint fracture had blocky inclusions (Fig. 7 (b)). Figure 8 was energy dispersive specttrometer (EDS) analysis of the welded joint fracture, its major elements were Fe, C, Si and etc., and the chemical mass percentage (%) in its primitive state was C 4.72, Si 0.26, Fe 95.02, respectively, while the mass percentage was C 4.97, Si 0.53, Fe 94.50 after the laser shock processing. The chemical mass percentage of the fracture in the primitive state was the same as that after the laser shock processing, showing that welded joints in X70 steel pipeline by laser shock processing still maintained the original fine mechanical properties in primitive state.



(a) In primitive state



(b) After laser shock processing

Fig. 8. Energy spectrum analysis of the fracture in welded joints in X70 steel pipeline

(1) After laser shock processing, a grain refining strengthened layer with compressive residual stress field was formed in the surface of welded joint in X70 steel pipeline, which improved the tensile properties of the welded joint.

(2) Laser shock processing had obvious influence on the tensile properties of welded joint in X70 steel pipeline. The welded joint in primitive state exhibited brittle fracture with less tearing edges. Although its tensile strength and yield strength had decreased after the laser shock processing, the fracture of welded joint was ductile rupture with a lot of tearing edges, and the toughness of welded joint increased.

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