FFEMS Fatigue & Fracture of Engineering Materials & Structures

doi: 10.1111/j.1460-2695.2011.01645.x

An investigation on the impact fatigue characteristics of valve leaves for small hermetic reciprocating compressors in a new automated test system

A. C. ALTUNLU[1,*], **I. LAZOGLU**[1], **E. OGUZ**[2] **and S. KARA**[3]

[1]*Manufacturing and Automation Research Center, Department of Mechanical Engineering, Koc University, Sariyer, Istanbul 34450, Turkey,* [2]*R&D Center, Arcelik A.S., 34950 Tuzla, Istanbul, Turkey,* [3]*Compressor R&D Center, Compressor Plant, Arcelik A.S., Eskisehir, Turkey*

Received in final form 4 October 2011

ABSTRACT This paper presents an investigation on the impact fatigue characteristics of valve leaves that are prevalently used in hermetic reciprocating compressors especially for the household type refrigerators. A unique automated impact fatigue test system has been designed and produced, which enables to carry out impact fatigue tests of the compressor valve leaves under the desired impact velocities. The test system incorporates a noncontact actuation, a data acquisition system and an acoustic-based damage detection technique, which continuously monitors the health of the structure. The damage detection system allows parametrical investigation on the impact fatigue life by detecting any possible damage and automatically terminating the test. The investigation relates the impact fatigue lifetime of the valve leaves with the impact velocity, asymmetrical impact, operation temperature, material type (carbon strip steel, stainless strip steel and new stainless strip steel grade) and tumbling operation duration. The observations show that the cracks have initiated from the edges of the valve leaf where is in contact with the valve plate. Subsequently, the cracks initially have propagated in the radial direction inwards the center of the impact area. Various failure cases have been resulted in by either a single crack or inter-related multiple cracks. Microscopic and metallographic observations have been performed on the specimens to enhance the understanding of the damage mechanisms. The investigation and introduced test system guide the design optimization of the valve leaves in terms of compressor performance due to the energy consumption and lifetime of the valve leaf.

Keyword compressor valve leaves; fatigue crack growth; fatigue test methods; failure analysis; impact fatigue.

NOMENCLATURE

N = Impact fatigue life
T = Hours of tumbling operation (nominal)
a_n = Crack length
$n = 1,2,3$ = Crack propagation paths

INTRODUCTION

Hermetic reciprocating compressors are used in especially heat, ventilation and air conditioning (HVAC) applications. Because environment friendliness and the energy consumption becomes a momentous issue, improving the performance of the compressor, which covers the main part of energy consumption, became a very important subject. The parameters that affect the compressor performance include; valve leaf dynamics, re-expansion volume, heat transfer, flow resistance, friction loss, the leakage caused by the piston and cylinder clearance.[1] The valve leaf controls the suction and discharge phases of the reciprocating compressors. Therefore, valve leaf characteristic plays one of the critical roles on the compressor performance.

During the suction and exhaust phases, the valve leaf vibration depending on the crank angle causes pressure oscillations. The pressure oscillations significantly influence the energy efficiency (coefficient of performance, COP) and the sound power level of the reciprocating

---

*Current Address: Applied Mechanics Section, Department Engineering Technology, University of Twente, 7500 AE Enschede, The Netherlands.
Correspondence: I. Lazoglu. E-mail: ilazoglu@ku.edu.tr

compressors, hence designing optimum valve leaf and processes after production is essential.

Valve leaves must maintain proper working properties in the lifetime of the compressor without failure. Valve leaves are experienced especially bending stresses and impact stresses during the work of compressors, therefore bending fatigue strength and impact fatigue strength of the reed valve play a deterministic role. On the other hand, choosing high bending fatigue strength strip steel for valve leaves could prevent bending fatigue failure. In addition, bending fatigue strength could be examined in commercial fatigue testing devices. In this regard, the parameters, which affect the impact fatigue life, need investigation in a special impact fatigue testing system.

A review of the studies in literature shows that the impact fatigue phenomenon and experiments have been researched from various viewpoints. Nakayama and Tanaka carried out impact fatigue experiments on plain and notched carbon steel, aluminum and duralumin specimens in push–pull type pulsating impact load applier test machine,[2–4] Iguchi et al.[5] performed impact fatigue experiments on smooth and notched low carbon steel in a forced falling hammer type testing machine,[6] Futakawa et al. investigated impact bending of fine-grained isotropic graphite material in pendulum type repeated impact bending machine,[7] Dumitru et al. introduced a guided hammer with cam mechanism apparatus for testing torsional impact fatigue of carbon steel shafts.[8]

The response of surfaces for repeated impact loads was examined in terms of free falling particle on the metallic material specimen surfaces,[9] bullet-shaped projectiles impact using magnetic fields,[10] solid particle streams on the specimen surface,[11–13] creating repetitive impulsive loading with hammers driven by electric motors,[14,15] impact of steel particles with a rotating arm apparatus,[16] electromagnetically forced cantilever beam which had a ball-bearing hammer on the tip for studying repeated impact wear.[17]

Beside investigations in the test systems, Glaeser[18] diagnosed the impact fatigue failure of reed valves used in reciprocating compressors. The failures were observed with the aid of scanning electron microscope (SEM). The crack origins of the valve leaf occupied on the impact area, was formed by the contact of valve plate during closure, thus the failure was described as impact fatigue. A strip steel of higher impact fatigue strength material grades and tumbling is recommended for preventing failures.

The influence of surface treatments were researched by Svenzon[19] and Soedel.[20] Tumbling and shot peening were stated as the methods of surface treatments. On the surface of flapper valve steels, introducing compressive residual stresses and reducing or eliminating the surface defect stress raisers by the surface treatments, significantly improved the bending fatigue strength.[19,20] Chai[21] emphasized that tumbling or tumbling and shot peening operation as a surface treatment, increased hardness near the surface by plastic deformation and introduce compressive residual stresses that lead higher resistance to fatigue crack initiation.[21]

The impact fatigue, bending fatigue, and wear pose are considerably challenging damage mechanisms in a comprehensive design of the suction valves in refrigerators. A novel automated impact fatigue test system, which provides a precise investigation by a noncontact actuation, a crack detection technique and a test trigger mechanism, is presented in this article. The system simulates the real working behavior of valve leaves during the lifetime and various critical issues on the lifetime of the compressor suction valve leaves for refrigerators have been examined. The automated impact fatigue test system is a unique system that enables to investigate the impact fatigue characteristics of thin strip specimens such as compressor valve leaves subjected to repeated impact loads.

EXPERIMENTAL SETUP

Description of the test system

The test system has been designed in such a way that the impact fatigue life characteristics of the compressor valve leaves could be investigated and crack initiation detection using a microphone was implemented in the system. Extensive impact fatigue tests have been performed in the test system (Fig. 1) that is schematically shown in Fig. 2.

The real working behavior of valve leaves in the compressor was simulated with a noncontact actuation. The test system included compressor valve plate and fixture, solenoid valve, pressure regulator, filter, pressure sensor, function generator, DC power supply, cycle counter, PC & data acquisition system, microphone, signal input/out (I/O) connector block, transistor circuit, Laser Doppler Vibrometer (LDV), LCD Screen for CCD camera in LDV.

In the test system, original valve plate and valve leaf couple was utilized through the experimentation in order to simulate the real behavior in the compressor. A fixture was designed to mount the valve plate. The main principle of the system is creating pulsating airflow through the solenoid valve. The inlet pressure air supplied from the main compressed air source is filtered with a good particle separation and regulated with minimal hysteresis in order to avoid pressure oscillations. The solenoid valve is actuated in the desired frequency by generating reference signals with the aid of function generator in order to simulate opening and closing movement of the valve leaf. The numbers of impacts are displayed by an electronic cycle counter, which is connected to the function generator. The inlet pressure is measured and displayed by a

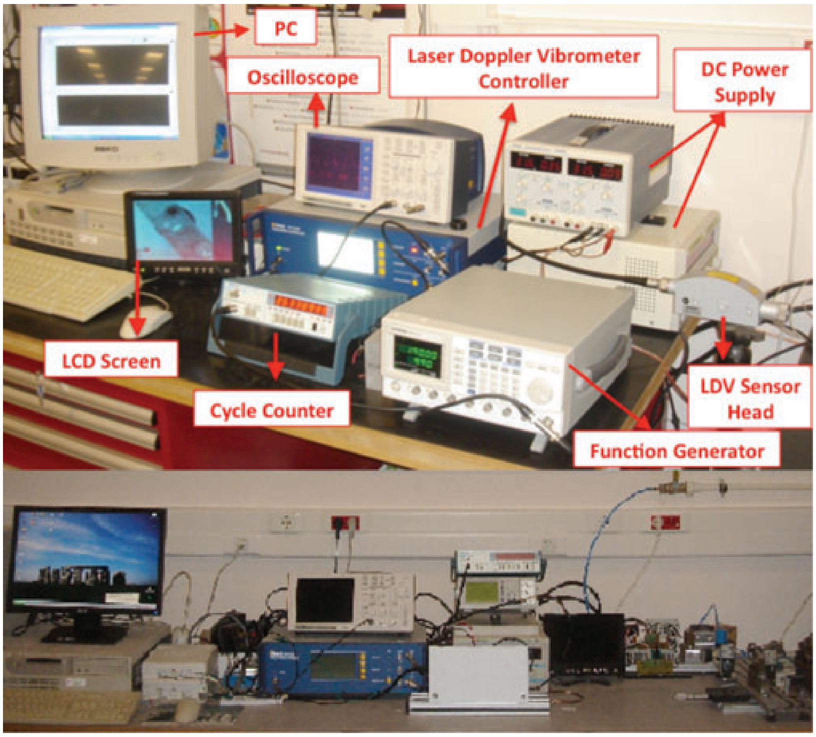

Fig. 1 Test system.

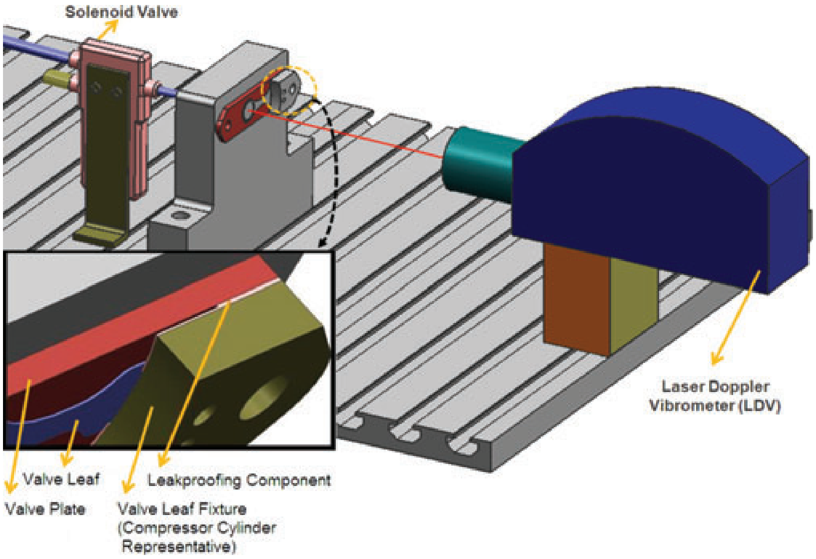

Fig. 2 Schematic display of the test system.

pressure sensor. When a failure occurs on the specimen due to impact fatigue, the failure detector terminates the experimentation. Graphical programming environment was created with LabVIEW software for data acquisition, signal processing and triggering mechanism. The impact fatigue experimental setup provides an automation system for controllable impact fatigue tests.

Crack detection technique

A crack detection technique has been developed to discern the crack initiation during the experimentation process. The sound pressure generated by valve leaf impacts is acquired via a microphone. Microphone sound pressure input that is collected from the valve leaf repeated impacts on the valve plate, acquired and processed by LabVIEW software. The microphone sound level signal is proportional with the impact energy of the valve leaf. Acquired sound pressure in the time domain converted to the frequency domain by Fast Fourier Transform (FFT) in LabVIEW. The LabVIEW program detects the maximum amplitude at the actuation frequency.

Because the sound pressure amplitudes tend to change as the crack initiates, the sound input data is compared

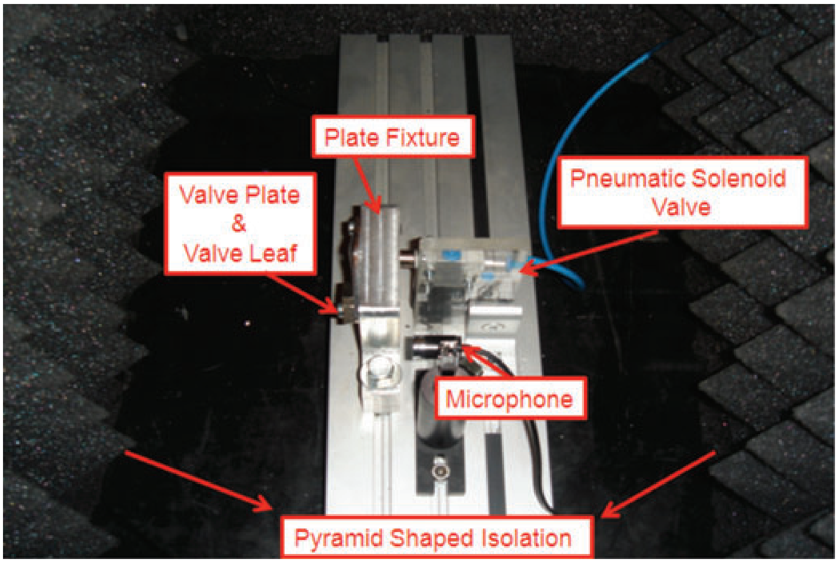

Fig. 3 Crack detection method.

with the following acquired input data at the actuation frequency to detect any damage. Initially, a controlled tuning experiment for each material type has been performed to define the criteria for failure. During the experiment, a pilot valve leaf has been periodically examined under the microscope until a first visible crack has been observed, at which the difference between the two acquired input data has been defined as the criterion for damage occurrence. These damage criteria have been used as a reference for the further testing. If the damage criterion is satisfied, the algorithm automatically terminates the data acquisition and the impact fatigue lifetime of the specimen, corresponding date & time is saved and displayed on the computer. Through the DAQ device, a signal is generated automatically as the failure occurs and I/O connector block is used for signal connection from DAQ device. A transistor circuit connected to I/O connector block terminates the experiment process when a failure occurs.

In the test system, a pre-defined critical crack length can be detected by re-adjusting the reference damage criteria. Consequently, the crack growth rate and the lifetime can be obtained by automatically terminating the program as the new criterion is satisfied and further crack propagation would be prevented. Additionally, a pyramid shaped isolation material has been used to cover the test system for the isolation from the external noise (Fig. 3).

Description of the temperature control cabin

The influence of the operation temperature, at which the valve leaves are experienced in the compressor, has been investigated. The experimental setup is placed in the designed temperature control cabin that is isolated from the environment in order to examine the impact fatigue life in various temperatures. Temperature control cabin includes an electrical resistance, halogen lamp, tempered glass windows, a PID controller and K-type thermocouple (Fig. 4). The temperature control procedure uses a

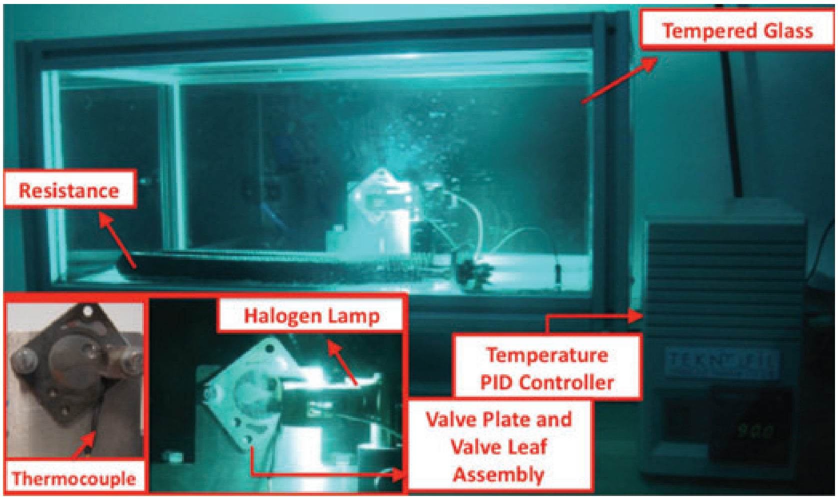

Fig. 4 Temperature control cabin.

Table 1 Chemical composition of strip steels

	Chemical Composition (nominal) %						
Material	C	Si	Mn	P	S	Cr	Mo
Carbon strip steel	1.00	0.30	0.40	0.008	0.0070	-	-
Stainless strip steel	0.38	0.38	0.50	0.018	0.0027	13.45	0.94
High-grade stainless strip steel	0.38	0.35	0.60	0.015	0.0035	13.58	1.01

Table 2 Mechanical properties of strip steels

	Mechanical properties (at 20 °C)	
Material	Min Tensile Strength $R_{\min}$ (MPa)	Max Tensile Strength $R_{\max}$ (MPa)
Carbon strip steel	1,990	2,030
Stainless strip steel	1,770	1,830
High-grade stainless strip steel	1,860	1,940

thermocouple, which is directly in contact with the valve leaf and connected to a PID controller, instantly measures the temperature of the valve leaf. Electrical resistance and halogen lamp are adjusted due to the controlling action of the PID controller to reach the desired test temperature.

Because the operating fluid temperature range of the solenoid valve is between −5 °C and 60 °C, the inlet air could not be preheated, so that the inlet air through the solenoid valve was at ambient temperature. Besides the electrical resistance, a powerful instant heating was directly exposed on the valve leaf by a 500 W halogen lamp. In the temperature control cabin, a special tubing and push-in fitting combination was used in order to avoid softening of the material by the high temperature. The equipments were located behind the steel valve plate fixture and the thermocouple was hidden behind the valve leaf fixture in order to prevent instant heat exposure of the halogen lamp. Experimental cabin was surrounded by tempered glass that is impact resistant and resistant to thermal stresses. During the tests, the applied stresses must first overcome the compression of the tempered glass, which was created by the tempering production technique, before any possible fracture. As a consequence, a reliable test system was provided.

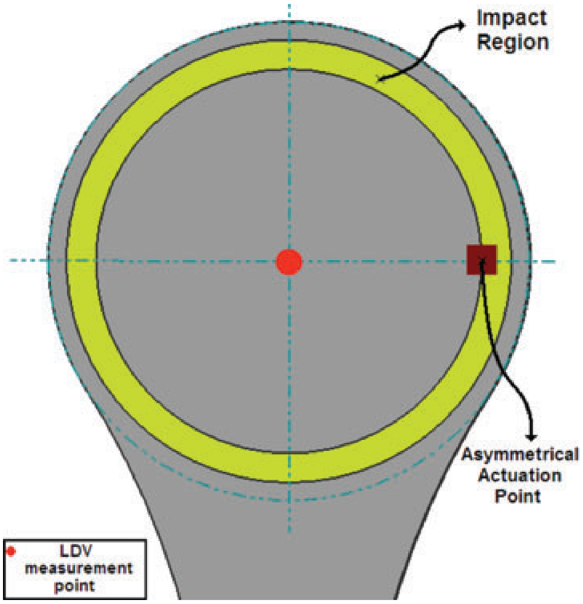

Fig. 5 Experiment specimen representation.

METHODOLOGY

Material

The materials used in the tests were hardened and tempered carbon flapper valve strip steel, a martensitic stainless strip steel and high-grade stainless steel. Chemical composition of the materials was presented in Table 1, and mechanical properties, which have been obtained from Arcelik A.S., were listed in Table 2. The structure of the specimen is tempered martensite. Grain of the material was longitudinal oriented in production. Valve leaves used in hermetic reciprocating compressors for refrigeration were investigated.

Experimental procedure

The experiments were performed at room temperature in dry environment conditions. The impact velocity and displacement of the specimens, which characterize impact fatigue lifetime, were measured simultaneously from the center of the valve leaf impact region via LDV. The airflow pulses application point in asymmetrical impacts experiments can be seen in Fig. 5. The tests were performed at 250 Hz. A microphone is used to detect the failure when a fracture occurs at the edge of the specimen. The automated system prevents further damage on the specimen by terminating the test and the impact fatigue life of the specimen is recorded. During the tests, stroboscopic motion of the valve leaves was displayed on the LCD screen with a CCD camera mounted. Microscopic and metallographic observations were carried out. The flowchart of the system is shown in Fig. 6. In addition, the impact fatigue life tests were performed at 70 °C, 90 °C and 110 °C in the temperature control cabin.

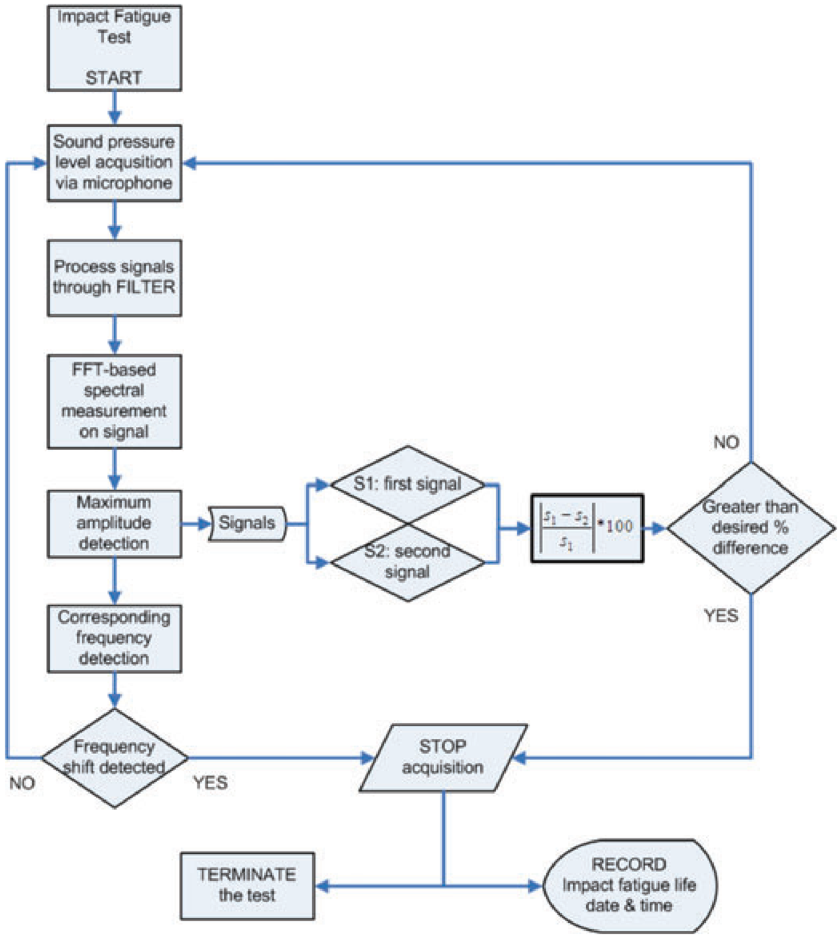

Fig. 6 Flowchart of the system.

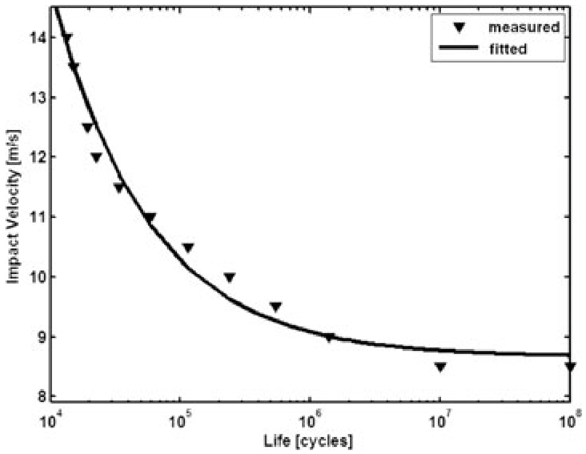

Fig. 7 Endurance curve of carbon strip steel.

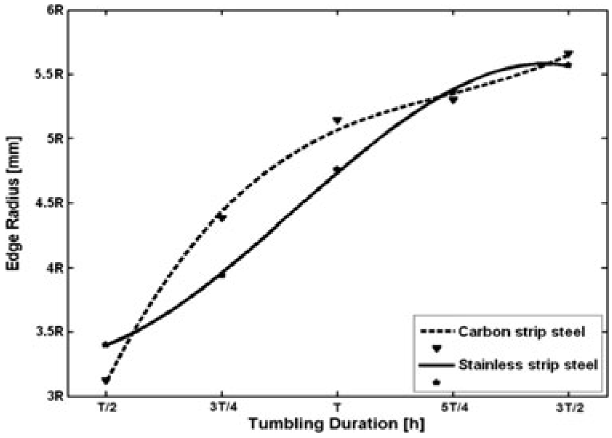

Fig. 8 The Effect of tumbling duration on edge radius.

RESULTS AND DISCUSSION

Carbon strip steel impact fatigue response curve

The valve leaf and the corresponding number of cycles to failure are related the impact velocity. Impact velocity versus lifetime plot provides a tool for designers to characterize the specimen behavior under specific impact fatigue conditions. The endurance curve (Fig. 7) includes an investigation for various impact velocities and the averaged impact fatigue lifetime of the specimens for each level of impact velocity.

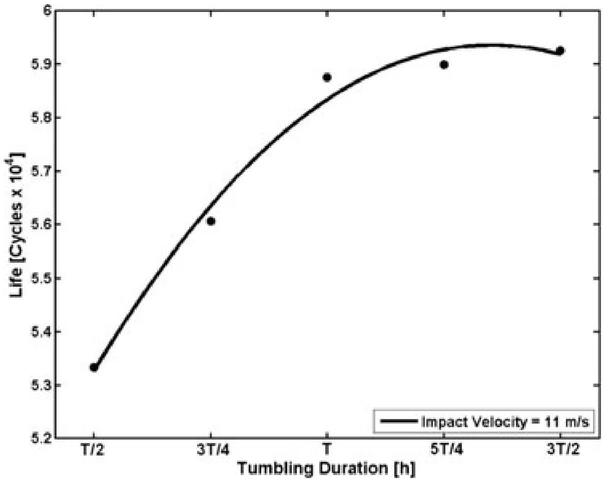

Fig. 9 The effect of tumbling duration on impact fatigue life of carbon strip steel.

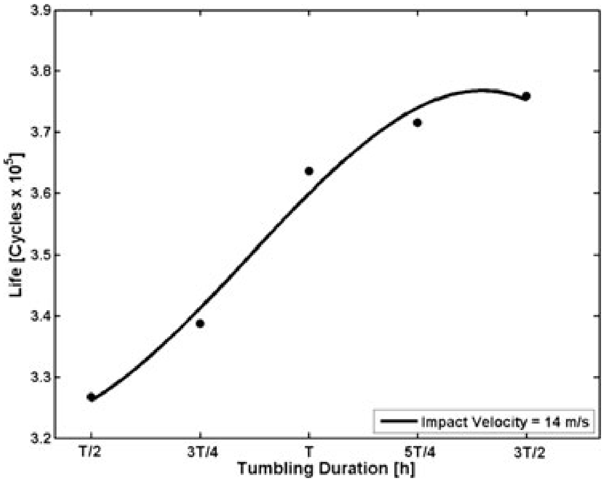

Fig. 10 The effect of tumbling duration on impact fatigue life of stainless strip steel.

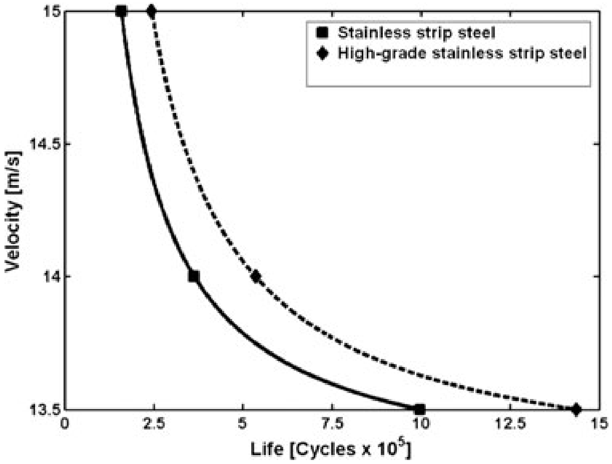

Fig. 12 Comparison of stainless strip steel and high-grade stainless strip steel.

Edge radius effect

After manufacturing of the valve leaves, a tumbling operation is performed to clean the burrs and eliminate possible fracture regions at the edges. Tumbling operation provides smooth and rounded edges and removes manufacturing defects that behave as stress raisers. The duration of the tumbling process, which affected edge radius and impact fatigue life of the valve leaves, was investigated for five levels. After manufacturing process, the edge radius of the specimens was measured on three randomly selected specimens for every level of tumbling duration shown in Fig. 8. Tumbling duration was correlated with the impact fatigue life for carbon strip steel (Fig. 9) and stainless strip steel (Fig. 10).

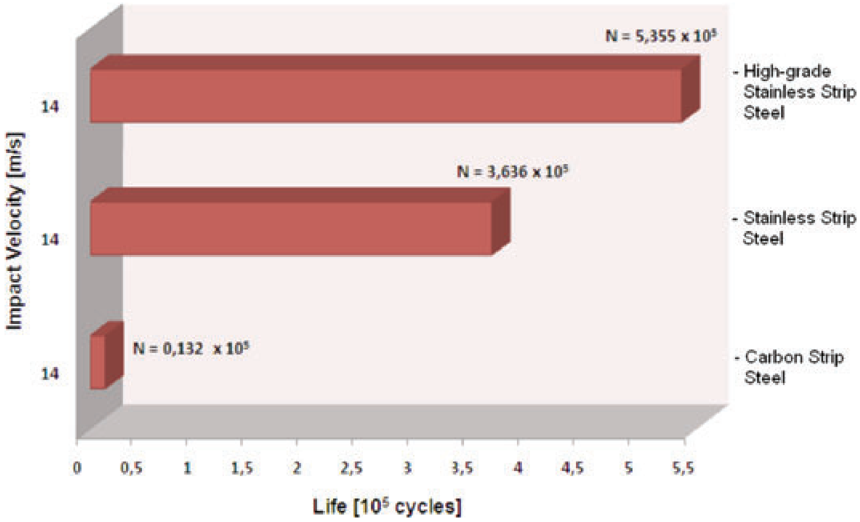

Fig. 11 Comparison of impact fatigue life.

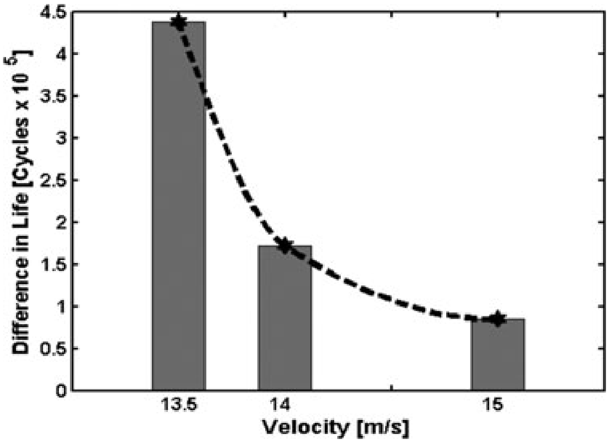

Fig. 13 Difference in lifetime between stainless strip steel and high-grade stainless strip steel.

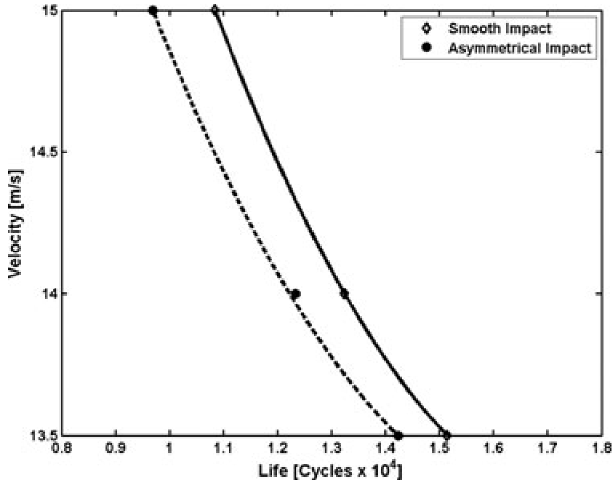

Fig. 14 Asymmetrical and smooth impact comparison.

Impact fatigue life comparison

The tests were performed so that the influence of the strip steel used in compressor valve leaves was investigated in terms of impact fatigue life. Three types of material were tested, carbon strip steel, stainless strip steel and high-grade stainless strip steel. The lifetime of three different strip steel materials were compared at 14 m/s impact velocity and presented in Fig. 11. It can be easily seen from figure that stainless strip steel and high-grade stainless strip steel was superior to carbon strip steel. In addition, stainless strip steel and high-grade stainless strip steel were compared at three different impact velocity

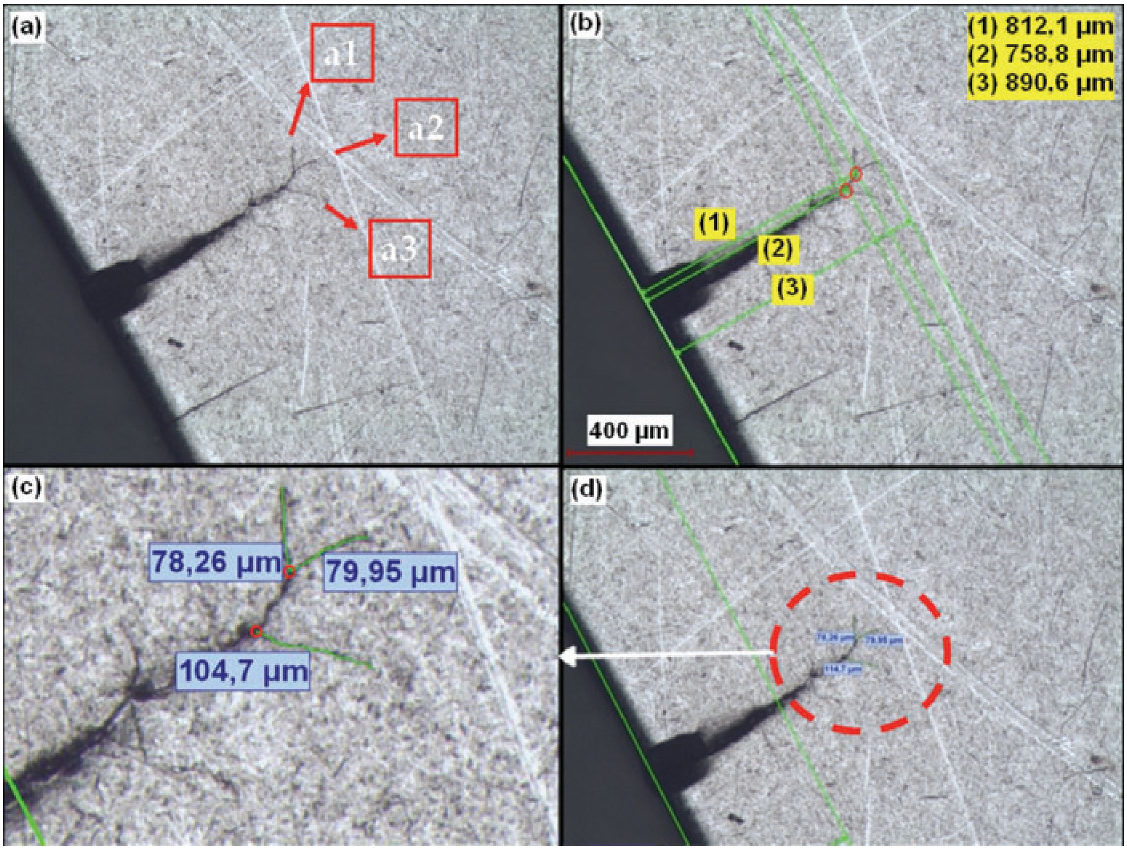

Fig. 15 Crack length microscopic observation (50×).

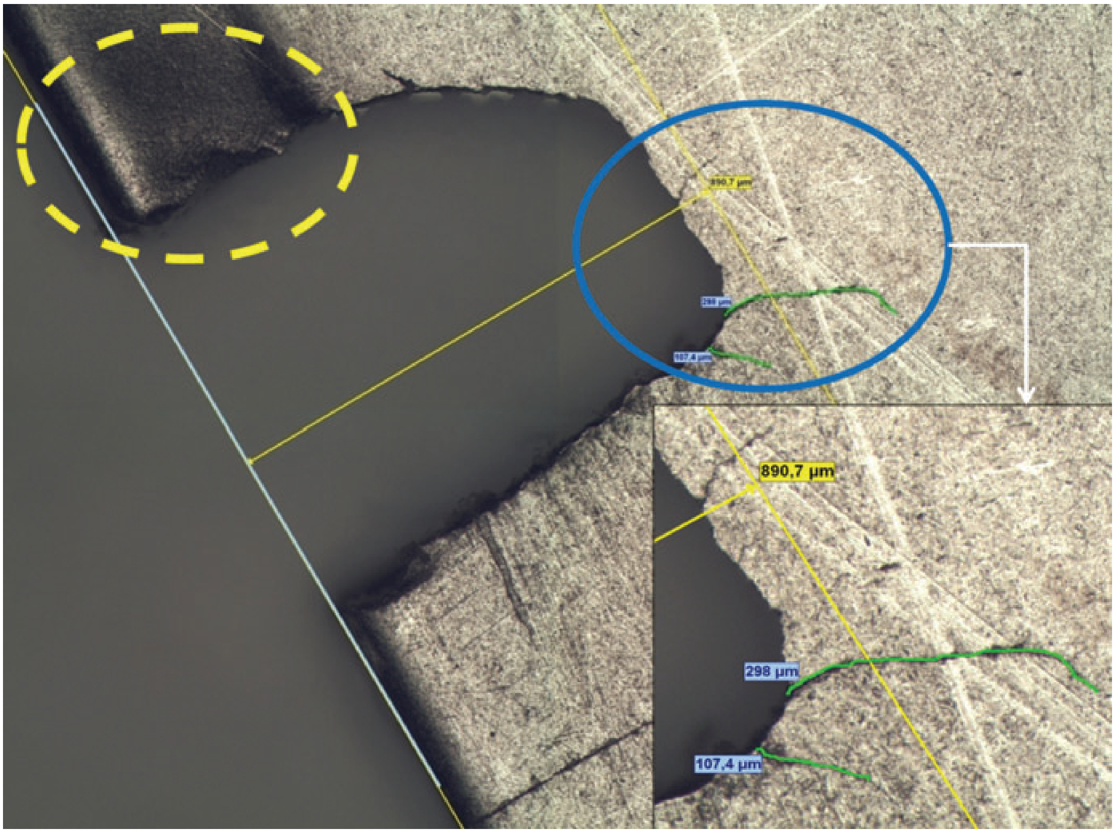

Fig. 16 Microscopic observation of final fracture at the edge (100×).

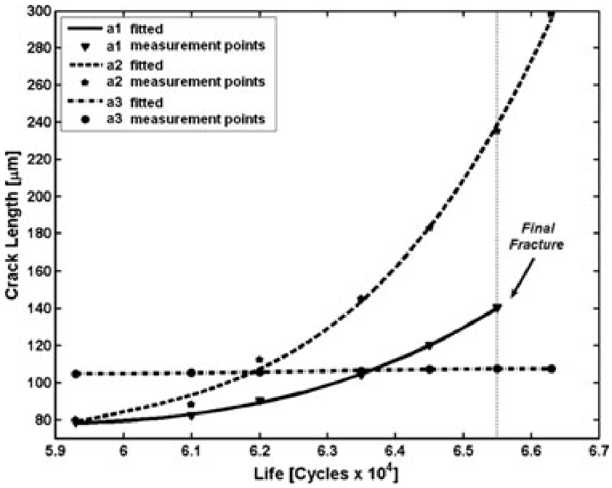

Fig. 17 Crack length measurements for a_1, a_2, a_3.

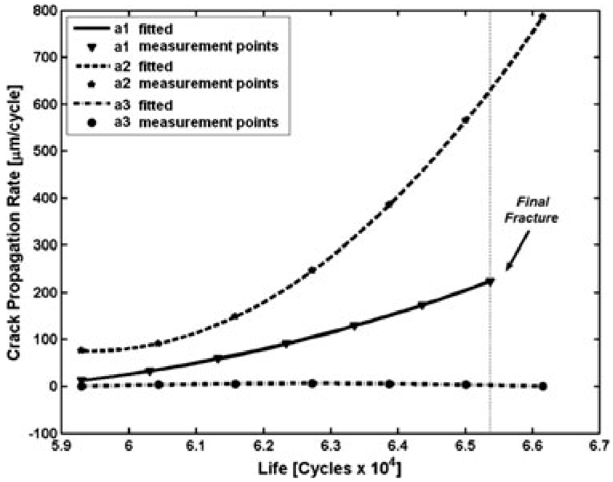

Fig. 18 Crack propagation rates of a_1, a_2, a_3.

levels, at 15, 14, 13.5 m/s. High-grade stainless strip steel impact fatigue strength was higher than stainless strip steel. The difference between the lifetimes of the two types of materials decrease as the impact velocity increased. The results were presented in Figs 12 and 13.

Asymmetric impacts

Although the impacts of valve leaves on the valve plate are predicted as smooth impacts, the variation in working condition of the compressor and the designs of other components can cause asymmetric impacts (Fig. 5). Asymmetrical impacts were investigated as working condition

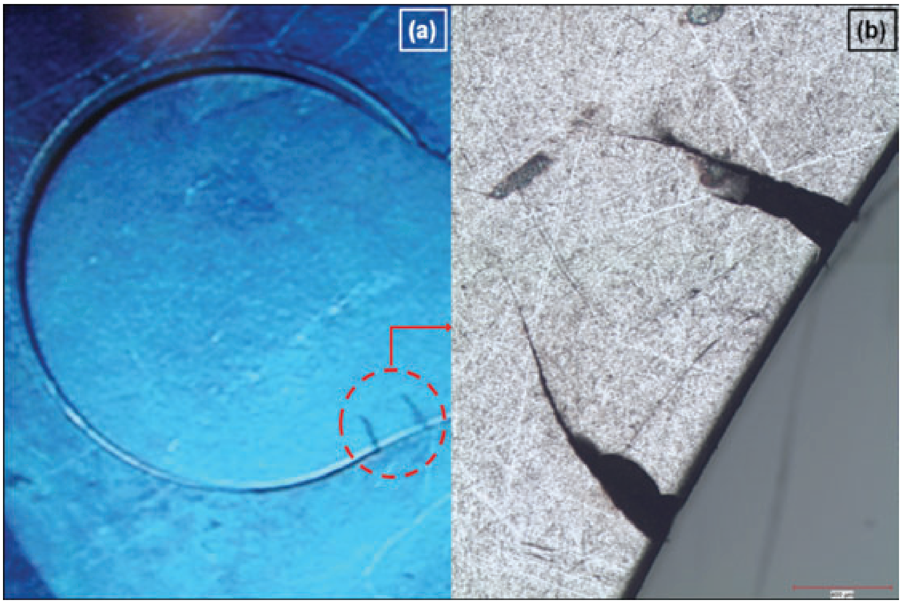

Fig. 19 Valve leaf double crack origin (a) top face (b) microscopic display of impact surface.

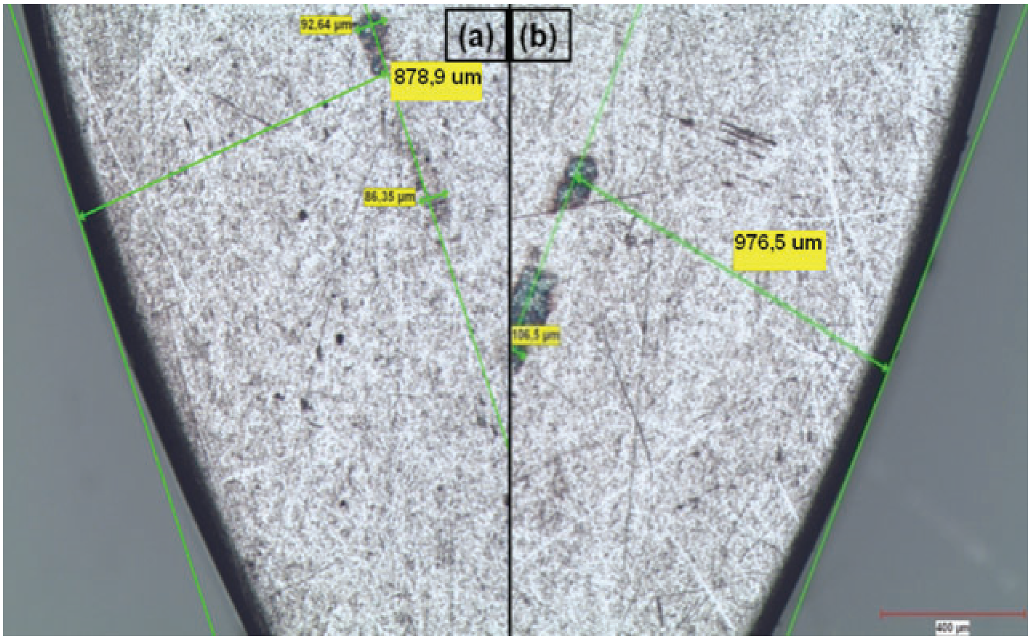

Fig. 20 Microscopic observation: (a) and (b) wear marks of symmetrical regions.

effect on the impact fatigue life and compared with the smooth impact lifetime in Fig. 14.

Crack length and crack growth rate

After an initial crack length was generated, the valve leaf was observed periodically under the microscope to visualize the possible crack initiation regions and propagation behaviors. The test performed at 15 m/s impact velocity. The crack length corresponded to the number of cycles were measured on the microscope. Three crack propagation paths were observed before the final rupture. The crack branching has taken place close to the impact region inner boundary (Fig. 5). The inner boundary is the projection of the valve plate orifice on the valve leaf that is 1,050 μm distant from the edge. The observed paths were named as a_1, a_2 and a_3 (Fig. 15). The catastrophic final fracture was occurred in the direction of a_1 as seen in

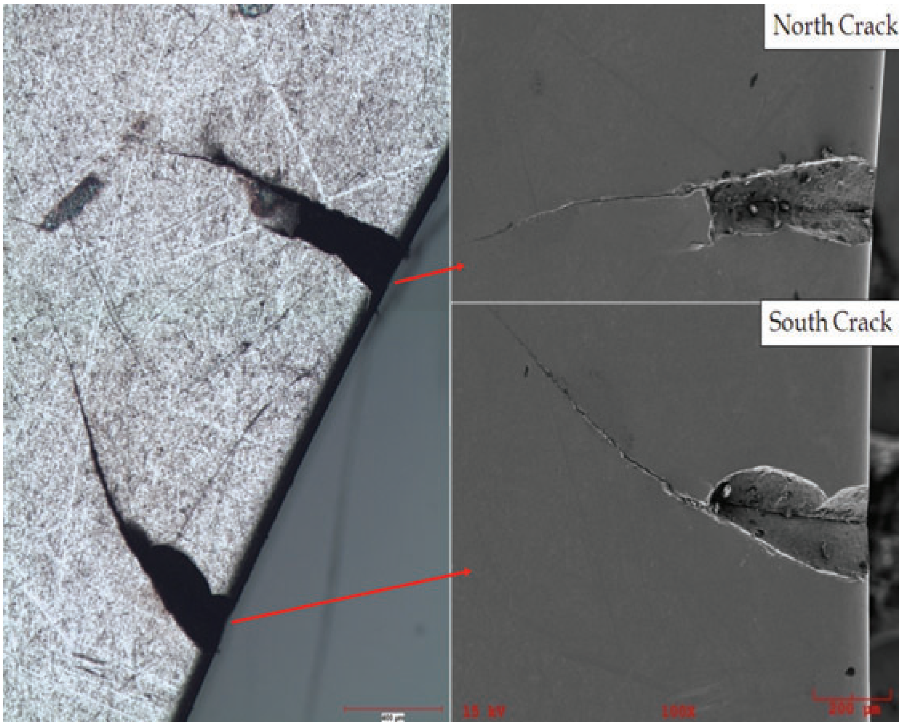

Fig. 21 Microscopic and SEM observation.

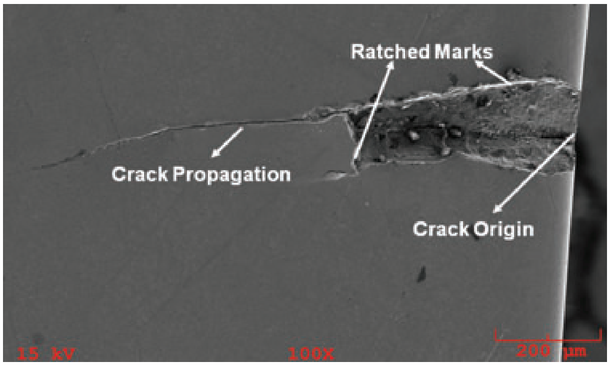

Fig. 22 SEM observation: north crack.

Fig. 16. The measured crack lengths versus corresponding number of cycles were shown in Fig. 17. The crack propagation rates were calculated and presented in Fig. 18, crack path a_2 had higher rate than a_1 whereas a_3 had a relatively low rate. The magnitude of cyclic plastic deformation due to impact fatigue loading intensified in the plastic zone at the crack tip of crack path a_2, the final fracture occurred on the path of a_1 (Fig. 18). It was observed that the edge of the valve leave, where the final fracture occurred, exposed a highly plastic deformation while the chip was torn away. The region can be seen from Fig. 16 and was marked with dashed circle. Because manufacturing tolerances cause slightly variations in the assembly of the valve leaf and valve plate, the crack growth rate presented below is unique for this sample.

Optical microscope and SEM observations

The SEM observations were performed in order to clarify the crack initiation and propagation mechanism. The stroboscopic image and microscopic image of the double crack originated specimen was shown in Fig. 19. The distances were measured between the edge of the valve leaf and the wear marks from the symmetrical regions of the valve leaf shown in Fig. 20. The difference in the measured distances was a remark that the impact area was altered during the testing. Therefore, a complex damage mechanism was generated. The alteration of the impact area can be caused by the design and manufacturing tolerances of the valve leaf and the valve plate.

The microscopic observation was compared with the SEM observations (Fig. 21). The impact surface (Fig. 22) and nonimpact surface of the north crack with crack origin (Fig. 23) were presented. In addition, the impact surface (Fig. 24) and nonimpact surface with crack origin (Fig. 25) of the south crack were presented. Fracture surface topology was investigated for both north and south cracks (Fig. 26) with fractographic observation.

SEM observations were performed to define the regional microstructure around the crack and the original valve leaf. After metallographic preparation and etching

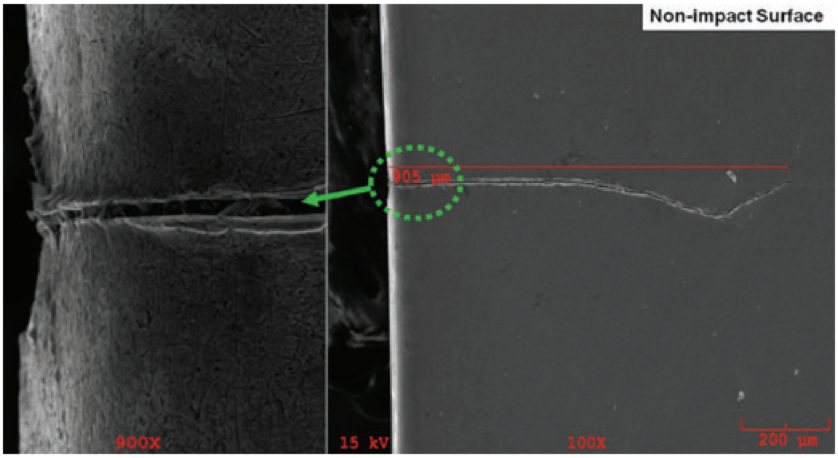

Fig. 23 SEM observation: north crack origin.

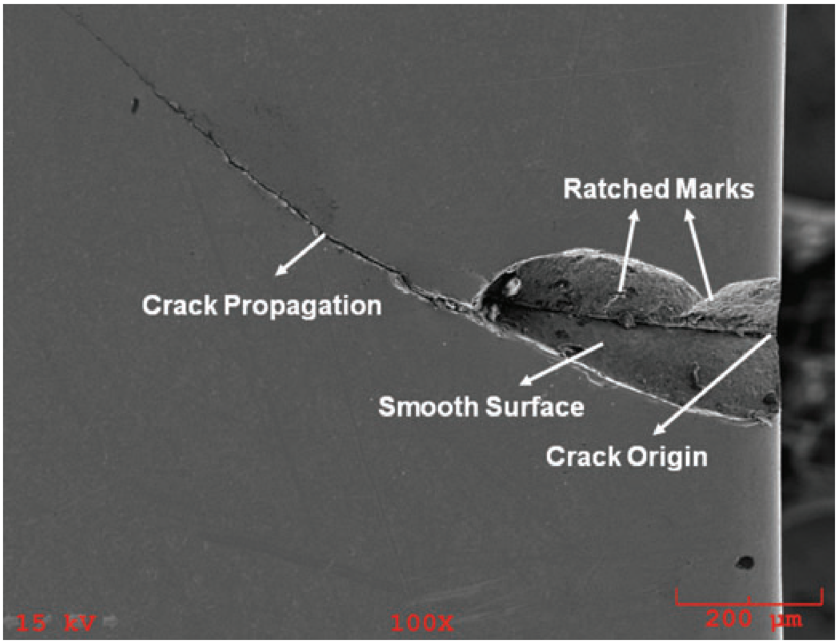

Fig. 24 SEM observation: south crack.

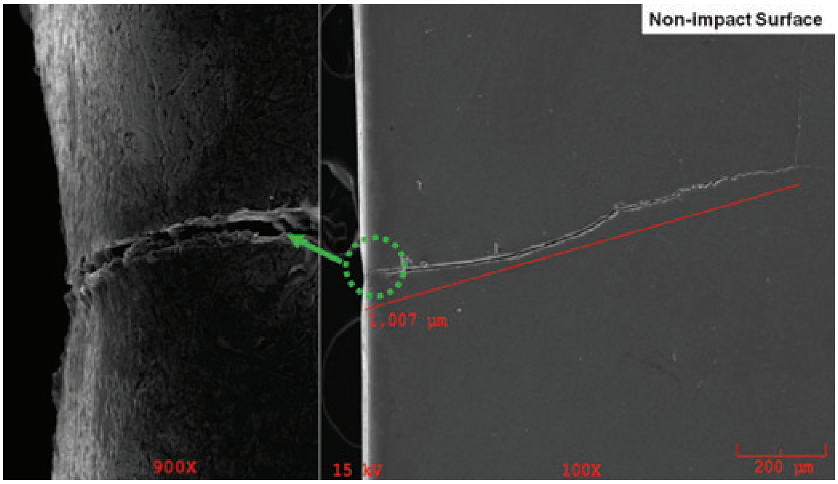

Fig. 25 SEM observation: south crack origin.

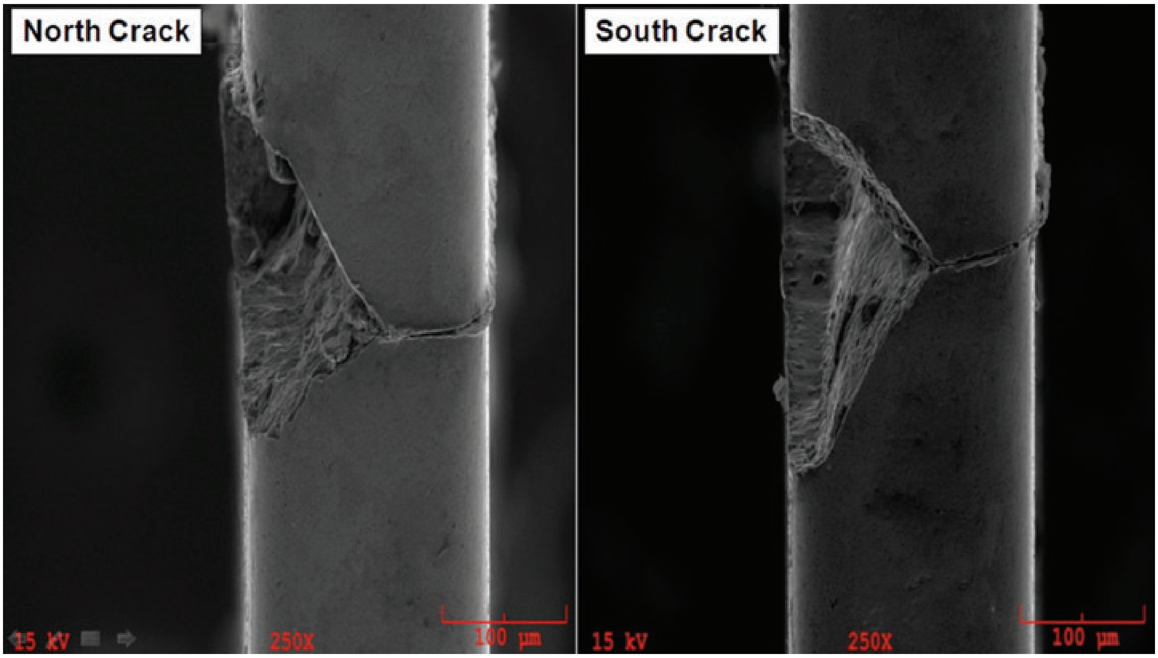

Fig. 26 SEM observation: fractography.

operation, carbon strip steel microstructure could be seen in Fig. 27 and the branching region in Fig. 28. It can be seen from the figures that the microstructure consisted of a fine-grained martensitic matrix with smoothly distributed carbides. Three regions were examined in terms of microstructure as depicted in Fig. 27. Regional microstructures crack origin (a), branching point (b) were compared with original microstructure (c) in order to understand the influence on the crack mechanism.

High-speed camera observation

The high-speed camera observations were performed on a pre-cracked specimen at 40,000 fps for the crack propagation characteristics and the representative frames in the sequence were presented in Fig. 29 while the test actuation frequency was 200 Hz. The focus area was exposed to a powerful light and different reflection degree of light on upper and below part around the crack was observed.

The influence of operating temperature on the impact fatigue life

The experiments were performed on the valve leaves around the operation temperature in the compressor and the influence of temperature on the impact fatigue lifetime was investigated. The tests carried out carbon strip steel with the original valve leaf design. Various impact velocities were tested at 90 °C ± 20 °C and the impact velocities were compared in terms of impact fatigue lifetime shown in Fig. 30. Experiments showed that an increase in the temperature slightly decreased the impact fatigue life in the test temperature range; in addition to that there was no clear difference between the impact fatigue lifetime at 70 °C and room temperature.

CONCLUSIONS

This paper introduced a new unique automated test system that enables to carry out a comprehensive investigation on impact fatigue lifetime of compressor valve leaves while enhancing the understanding of the impact fatigue characteristics of thin strip specimens under repeated impact loads. The main findings and outcomes of this study can be concluded as follows:

1. This paper introduced a new automated impact fatigue test system, which was designed and fabricated in order to enable extensive impact fatigue tests. The errors caused by operators were avoided by the automation system and provided reliable results. Impact fatigue tests were performed on carbon strip steel, stainless strip steel and high-grade stainless strip steel.
2. The form of the response curve of carbon strip steel exhibits a level off regime at 10^7 cycles when subjected to impact fatigue loading. As the impact velocity increased, the impact fatigue life of the specimens was decreased significantly.
3. The influence of the tumbling (surface treatment) duration was investigated and was related with the impact fatigue life. The edge radius of carbon strip steel

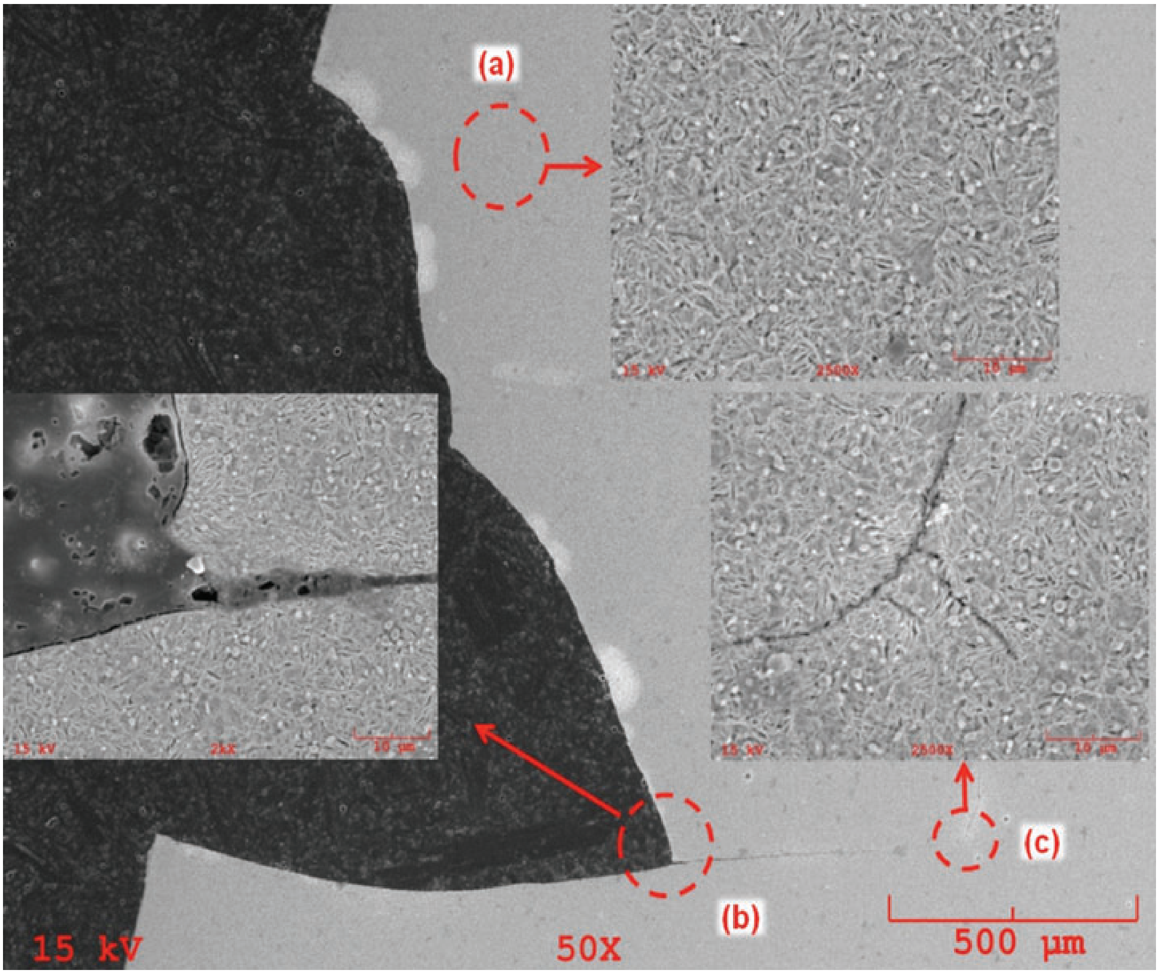

Fig. 27 Regional microstructure by SEM (a) crack origin, (b) branching point, (c) original microstructure.

leveled after "nominal (T)" hours of tumbling operation on the other hand stainless strip steel leveled after "5T/4" hours of tumbling operation. Long enough tumbling operation enhanced impact fatigue properties by smoothing the sharp edges of the valve leaves.

4 The tests showed that there was a considerable difference in impact fatigue strength between carbon strip steel and two martensitic stainless grades, stainless strip steel and high-grade stainless strip steel. The difference between the lifetimes of the two martensitic grades was decreased while the impact fatigue velocity was increased.

5 The variation of the compressor proper operation conditions and the design of other components can cause asymmetrical impacts that reduce the impact fatigue life of the valve leaf. It was observed that the cracks initiated at the region where air pulses were applied on Fig. 5.

6 The observations on the crack initiation and propagation phases for the valve leaves, which were exposed to cyclic impact loads, are presented. Regarding to the experiments, the cracks have initiated from the edges and tended to propagate in the radial direction inwards the center of the impact area. Subsequently, various scenarios can be induced by damage mechanisms leaded by

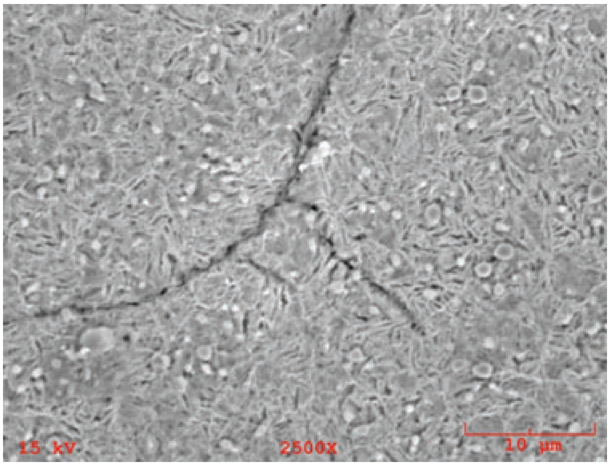

Fig. 28 Branching along the crack path by SEM, Region (c).

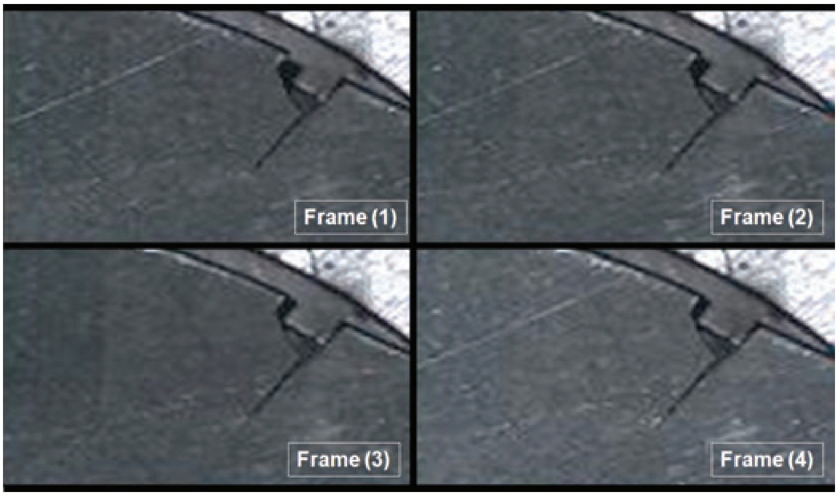

Fig. 29 High speed camera representative frames in the sequence at 40,000 fps for a pre-cracked specimen.

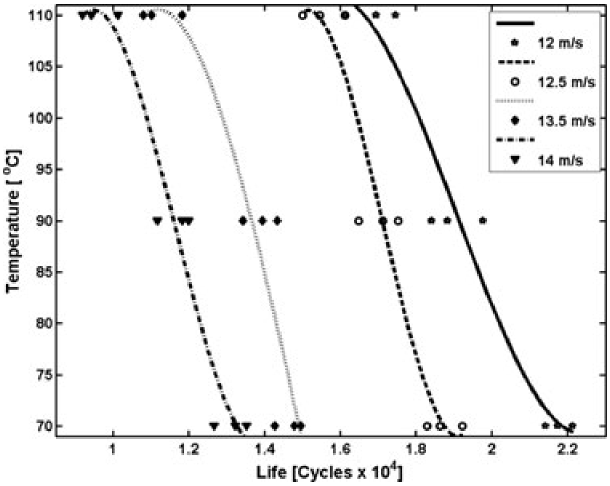

Fig. 30 The influence of temperature on the impact fatigue life of carbon strip steel.

either a single crack or inter-related multiple cracks. The possible subsequent cases are driven by a single crack growth causing the final rupture or multiple cracks branched from a single crack or multiple crack initiation from the edge and propagation together until one has been arrested and the other causes the final rupture. Because the designed manufacturing tolerances of the valve leaf and the valve plate results in various assembling positions on each other, the impact area on the valve leaves can be slightly tentative. Although the relative position of these two components has small variation, the stress waves generated by the cyclic impact loads can be changed and leading to stochastic damage behaviors in the valve leaves.

7 Throughout the experiments, with the aid of stroboscopic displays and CCD camera observations it can be concluded that cracks initiated at the edge of the valve leaves and sometimes there were more than one crack origins at the edges. The origins could collapse each other or grew independently until one of them dominated over the other. In some situations the crack propagated to the tip direction, subsequently formed a fracture, after that the propagation mechanism reversed and propagated to the root direction. The travel of the crack, after nucleation at the edge, is strongly depended on the valve leaf geometry and occupation of the valve leaf and plate. Because crack origins were died away because of the inversely propagation mechanism, the final fracture contour misled the observers for diagnosing the failure of the valve leaves which experienced in the compressors.

8 SEM observations showed that the cracks have been nucleated at the edge and a small part has been torn away. Subsequently, the damage has continued with a surface crack that has propagated on the impact area plane and penetrated through the thickness. A particle has been torn away by the surface crack advancement. And further damage has been leaded by new crack formation initiated from the previous damaged area.

9 Microstructural observations showed that the regions around the crack origins, along crack paths and in branching points had the same microstructure as the original microstructure of the valve leaf.

10 The combination of the design and the manufacturing tolerance values of the two critical components, valve leaf and valve plate resulted in an inhomogeneous occupation. That causes slightly asymmetrical impact velocity profile because of the unsymmetrical impact region generation of the valve leaf. Consequently, the valve damage mechanism and the impact regions were varying due to the various occupations.

11 Mode-I and Mode-III crack propagation was encountered during high-speed camera observations. The mixed mode crack growth on the valve leaf was created by the impacts.

12 A reliable temperature control cabin, which provides testing impact fatigue at various temperatures, introduced. It was found that the impact fatigue life of the carbon strip steel valve leaves was slightly decreased as the testing temperature was increased; however, the tests showed that impact fatigue life at 70 °C and room temperature were almost same.

Acknowledgment

The authors acknowledge the Ministry of Industry and Trade of Turkey and Arcelik A.S. (SANTEZ Project No.: 2.STZ.2006- 1) for their support on this project.

REFERENCES

1 Xin, R. and Hatzikazakis, P. (2000) Reciprocating Compressor Performance Simulation. *Proceedings of the International Compressor Engineering Conference at Purdue University*, Vol. V-I, pp. 1–9.

2 Tanaka, T. and Nakayama, H. (1973) Studies on impact fatigue, Part I. *Bull. JSME* **16,** 1814–1828.

3 Tanaka, T. and Nakayama, H. (1974) Studies on impact fatigue, Part II. *Bull. JSME* **17,** 1379–1388.

4 Tanaka, T. and Nakayama, H. (1975) Studies on impact fatigue, Part III. *Bull. JSME* **18,** 1365–1374.

5 Iguchi, H., Tanaka, K. and Taira, S. (1979) Failure mechanisms in impact fatigue of metals. *Fatigue Fract. Eng. Mater. Struct.* **2,** 165–176.

6 Taira, S., Iguchi, H. and Tanaka, K. (1979) Development of impact fatigue testing machine and some test results. *Proceedings of the 22nd Japan Congress Mater Res.*, Vol. **22,** pp. 181–186.

7 Futakawa, M., Kikuchik, K., Muto, Y. and Shibata, H. (1990) Impact bending fatigue and impact response behavior of a nuclear-grade graphite beam. *Carbon* **28,** 149–154.

8 Dumitru, I., Marsavina, L. and Faur, N. (2007) Experimental study of torsional impact fatigue of shafts. *J. Sound Vibrat.* **308,** 479–488.

9 Wellinger, K. and Breckel, H. (1969) Kenngrössen und Verschleiss beim Stoss metallischer Werkstoffe. *Wear* **13,** 257–281.

10 Bayer, R. G., Engel, P. A. and Sirico, J. L. (1972) Impact wear testing machine. *Wear* **19,** 343–354.

11 Sheldon, G. L. and Kanhere, A. (1972) An investigation of impingement erosion using single particles. *Wear* **21,** 195–209.

12 Lapides, L. and Levy, A. (1980) The halo effect in jet impingement solid particle erosion testing of ductile metals. *Wear* **58,** 301–311.

13 Cousens, A. K. and Hutchings, I. M. (1983) A critical study of the erosion of an aluminium alloy by solid spherical particles at normal impingement. *Wear* **88,** 335–348.

14 Studman, C. J. and Field, J. E. (1977) A repeated impact testing machine. *Wear* **41,** 373–381.

15 Rice, S. L. (1977) Reciprocating impact wear testing apparatus. *Wear* **45,** 85–95.

16 Rickerby, D. G. and MacMillan N. H. (1980) The erosion of aluminum by solid particle impingement at normal incidence. *Wear* **60,** 369–382.

17 Mahoney, N. J., Grieve, R. J. and Ellis, T. (1984) A simple experimental method for studying the impact wear of materials. *Wear* **98,** 79–87.

18 Glaeser, W. A. (1999) Failure mechanisms of reed valves in refrigeration compressors. *Wear* **225-229,** 918–924.

19 Svenzon, M. (1976) *Impact Fatigue of Valve Steel*. Acta Universitatis Upsaliensis, Uppsala, Sweden.

20 Soedel, W. (1984) *Design and Mechanics of Compressor Valves*. Office of Publications, Purdue University.

21 Chai, G., Zetterholm, G. and Walden, B. (2004) Flapper valve steels with high performance. *Proceedings of the International Compressor Engineering Conference at Purdue West Lafayette*, USA.