Failure Analysis and Repair of a Broken Extruder Shaft: A Case Study

Salem Ali Karrab and Mohamed Ali Ballem

***Abstract*—In this paper a failure analysis of a screw shaft used in a co-rotating intermeshing twin-screw extruder was carried out; furthermore, a detailed description for the repair procedure of the fractured part was presented. By means of the preliminary analyses of the failed shaft which includes a visual examination, appearance of fracture face, and photographic documentation of the fractured surfaces, and by summarizing and analyzing all relevant data it was possible to determine that the combination of torsion and bending forces was the cause of the failure. The shaft fractured with evidences of fatigue failure. Repairing of the fractured shaft was mainly performed by welding technique followed by suitable heat treatments and appropriate inspection methods. After repair process is completed, the extruder was put back into service, the recorded data during the trial and regular operations were satisfactory and within the design limits. Finally, in order to avoid future accidents and to prevent such problems in similar equipment, precautionary measures and recommendations were proposed.**

***Index Terms*—Bending, Failure, Fatigue, Torsion, Twin-Screw Extruder, Welding.**

I. INTRODUCTION

A. *Extrusion Process - an overview*

Extrusion is a technique that widely used for the continuous and intermittent manufacture of polymeric products, due to the ability of the preparation of highly uniform polymer melts at high rates. The molten polymer is forced through a die to produce the desired components of a fixed shape [1]–[4]. In polymers processing, extrusion using a screw extruder has been used for producing various products and compounds e.g. pipes, car parts, films, etc. Nowadays screw extruders are applied in various fields such as fiber spinning, film making, blow molding and injection molding; however, screw extrusion has a long history starting from the food industry to the rubber and plastics industries [5].

Extruders can be classified into two main categories: continuous and discontinuous (batch type) extruders. Discontinuous extruders operate in a cyclic way, whereas continuous extruders are able to developing a steady and continuous flow of material. The continuous extruders are divided into disk extruders, drum extruders and screw extruders [6]. Screw extruders are the main equipments for polymer processing, and based on the number of screws they are classified into single, twin and multi screw extruders; twin screw extruders can further classified based on the rotating direction, and the degree of intermeshing [7], [8]. Single screw extruders are most popular because of their low cost, simple designs, ruggedness, and reliability; they are widely applied in general polymer processing, such as injection molding, blow molding, and film making. Twin screw extruders are more efficient in the mixing ability and in providing homogeneous mixing of different ingredients, thus they are primarily used for polymer powder extrusion and compounding of various fibers, fillers and polymer blending prior to final molding [3], [5]–[9]. Multi-screw extruders mimic in some ways the geometry of the twin screw extruders, and are only limited to use in small scale production or special applications [5], [10].

B. *Twin Screw Extruder (TSE)*

Larger variety of twin screw extruders are offered in the market and as mentioned above these extruders may vary in their design and assembly, they could have parallel or conical screws that may rotate in same direction (co-rotating) or opposite direction (counter-rotating), furthermore the screws are called intermeshing if the distance between the shafts is less than the screw diameter, whereas they called non-intermeshing if the distance between the shafts equal to the screw diameter [8], [11].

The common components to all twin extruders include two screws, a barrel, a die, as well as drive motor and gearbox. The screws are responsible for accepting feed ingredients at the inlet, and forcing material through the exit of the extruder, known as the die. Screws are composed of a series of elements, which are assembled on a screw shaft; these elements have particular functions that can include conveying, kneading and mixing. The barrel contains the rotating screws, in general the walls of the barrel is smooth, but can also have helical or longitudinal grooves. The drive system is a direct current (DC) motor coupled with a gear box which transfer the available motor torque to the screws as illustrated in Fig. 1 [9], [11].

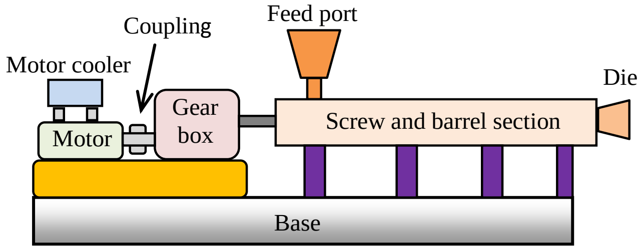

Fig. 1. A schematic illustration of main components of twin screw extruder

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Salem Ali Karrab is with Materials Science and Engineering Department, Faculty of Engineering, Misurata University, Libya, (e-mail: sgarrab@eng.misuratau.edu.ly).
Mohamed Ali Ballem is with Materials Science and Engineering Department, Faculty of Engineering, Misurata University, Libya, (e-mail: mohamed.ballem@eng.misuratau.edu.ly).

C. (ZSK) Type of Extruder

In 1957, Werner & Pfleiderer known today as Coperion GmbH developed a new generation intermeshing self-wiping co-rotating machine known as Zwei Schencken Knetter (ZSK 83) with screws installed above one another. Since that time many companies have delivered different types of twin screw extruders to the market; however, among the various available patterns, ZSK type of twin screw extruder remains functional over a wide range of processed materials, and therefore it is considered as forefather of all twin screw extruders. To meet the increasing quality requirements for polymers, ZSK designed various types of extrusion machines such as ZSK MEGAvolume and ZSK MEGAvolume PLUS [7], [12].

D. Aim of the Study

The aims in this study are twofold: First part describes the failure of one of the screw shaft that used in a co-rotating intermeshing twin screw extruder; a failure analysis was performed on the fractured shaft in order to determine the cause of failure in order to avoid similar accidents and to improve the performance and lengthen useful life of the studied extruder. The second part of the study provides a specific repair procedure based on welding as solution for the studied case instead of replacing the broken shaft with a new one which is costlier.

II. Case Description

A. Site Information

Raslanuf Oil and Gas Processing Company also known as RASCO, is located in Libya along the Mediterranean coast in the Gulf of Sidrah, about 650 km east of Tripoli. RASCO is the largest Oil Refinery in Libya, and it is a subsidiary of the state-owned the National Oil Corporation of Libya. Raslanuf Company built Ethylene and Polyethylene plants in 1988, the Ethylene Production Plant is the most important Plant with capacity of about 330,000 metric tons per year, whereas Polyethylene Plant producing about 55,000 Tons annually of low density polyethylene [13].

B. Equipment Data

The studied component in this case is a screw shaft of ZSK-240 extruder; the main technical specifications of the equipment according to vendor operating and construction manual are listed below:

Brand: Werner & Pfleiderer /Coperion Germany; Model: ZSK-240-R; Screws Type: Co-Rotating & Intermeshing; Year of Manufacturing: 1990; Motor 3300 KW; Main motor speed 1479 rpm; Max. Screw speed 270 rpm; Motor Torque per screw 70000 Nm; Screw Diameter 240 mm; and Max. L/D ratio Screw is 42.

C. Equipment History

The equipment is one of RASCO Polyethylene plants and it was under normal operation since 1997, abnormal vibration was recorded many times and therefore first major overhauled was in November 2000 under supervision of vendor. Wearing of screw elements was recorded by vendor specialist during overhauling period and metal powder was traced in the final product. Also as a result of bolts fastening, visco-seal rings were frequently broken and replaced. Reconfiguration of some screw element was carried out in order to improve final product quality. After completion of overhauling the equipment was put back into operation in December 2000. In January 2002 the extruder was tripped and shaft was broken.

III. Failure Analysis

A. Failure Background

When the extruder was tripped in January 2002, the shaft was found to break into two pieces at the coupling area approximately 550 mm from shaft end as shown in Fig. 2. After dismantling detailed inspection revealed severe mechanical damages in the barrel internal surface, and deep grooving up to 3 mm deep on screw elements as shown in Fig. 3, these were ascribed to overlap of both shafts on each other. This wearing in the screw elements and/or barrels creates a clearance up to approximately 26 mm. Also as a result of cracking, screw shaft tip was found broken and visco-seal ring was found damaged. Definitely it is valuable to mention that before failure an abnormal level of vibration was recorded many times, as well as metal powder was detected in the final product.

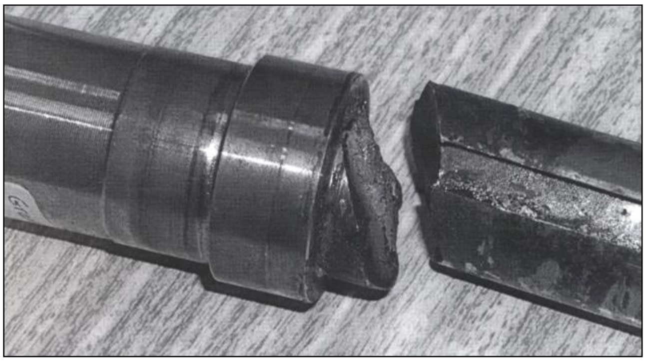

Fig. 2. General view of the failed screw shaft

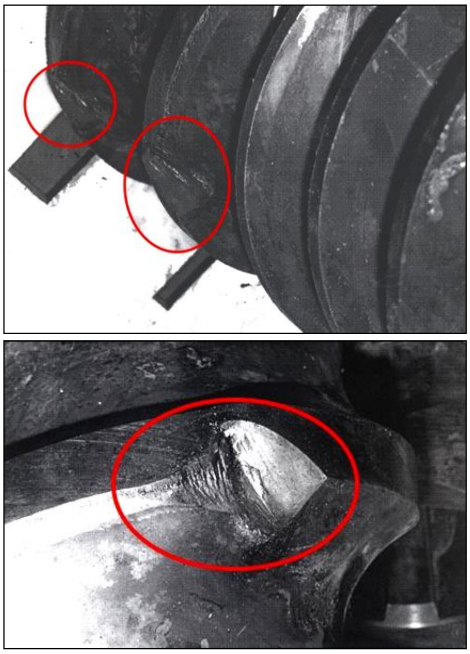

Fig. 3. Mechanical wear of the screw elements

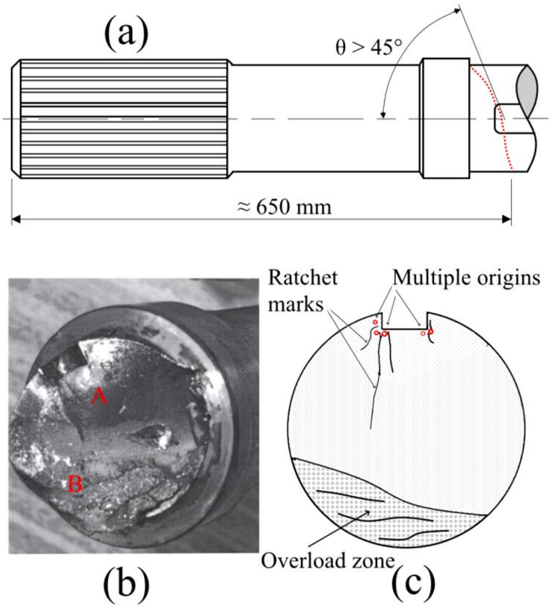

Fig. 4. (a) The approximate location of the fracture, (b) overview of the fracture surface, and (c) a schematic illustration of the fracture surface

B. Visual Observation of the Failed Screw Shaft

Visual examination is one of the first steps of any failure analysis process and remains the cornerstone of any failure examination; it is very important to perform this stage prior to any altering of the failed component. Photography and/or videotaping are used as visual documentation to obtain a permanent record of the studied case [14]. Fig. 2 shows a photograph of the broken screw shaft, it is obvious that the shaft failed at the keyway and the fracture travels across the shaft cross-section, climbing toward the stepped portion of the shaft. Further observation of the recorded photograph (Fig 2) revealed that the fracture surface is orientated with an angle greater than 45° with respect to the shaft centerline. The approximate location of the fracture is about 650 mm from the splined end of the shaft as illustrated in Fig. 4a; the appearance of fracture surface is shown in Fig. 4b, it is observed that the fracture surface consists of two different zones: the first zone is relatively smooth indicated with the letter A, while the second one has a rough surface and indicated with the letter B.

C. Screw Shaft Material

According to technical data provided in vendor operating and construction manual, the screw shaft of the twin-screw extruder is made of DIN 1.2344 tool steel. This type of steel is known as H13 tool steel, and it has the chemical composition reported in table I.

TABLE I: THE CHEMICAL COMPOSITION (WIGHT %) OF H13 TOOL STEEL, EXCLUDING IRON [15]

C	Si	Mn	Cr	Mo	Ni	Cu	V
0.32-0.45	0.80-1.20	0.20-0.50	4.75-5.50	1.10-1.75	0.30 max	0.25	0.80-1.20

D. Failure Cause, Mechanism, and Discussion

In the previous stages facts, data, and observations related to the studied case were collected, thus the remaining task in this investigation is the analyzing of this information in order to identify the potential causes of failure, and the failure mechanism which is the final goal of failure analysis. By revising the information that mentioned in failure background section it is clear that prior to failure there were unusual occurrences including, abnormal level of vibration, a trace of metal powder in the final product, and deterioration in the quality of final product; such evidence indicating that the extruder was operating in a bad condition, and it was only a matter of time until failure occurred. After dismantling the extruder, mechanical damages including wear in the barrel, wear in the screw elements, wear in the tip of the screw shaft, and too large clearance between the two screws and between the screws and the barrel were revealed. The worn out of the extruder parts and the presence of metal powder in the final product indicating possible touch between the screws and the barrel or between the rotating screws resulting in undue torsion stress on the shaft, while excessive vibration of the extruder is an indicator of misalignment which leads to creation of bending force acting on the shaft as well [16]. Since these forces are repeated every cycle, thus the combination of torsion and bending forces is most likely the cause of the fracture and the failure mechanism is fatigue.

Torsional-bending fatigue mechanism is further supported by carefully analyzing the data provided in visual observation section, beginning from the orientation of the fracture face with respect to the shaft centerline, when the angle of the failure surface is approximately 45° it is a clear indication that fracture is due to torsional fatigue [14], [17]–[20], however in the presented case the angle is midway between 45° and 90°, thus the failure was not only due to torsion force but the combination of both torsion and bending forces caused the fatigue failure [17], [18].

Close observation of the fracture surface shown in Fig. 4b revealed features of a typical fatigue failure surface; the cracks initiated at some points that have high stress concentration located at the corners of the keyway as illustrated in Fig. 4c; keyways are common stress raisers in shafts and probable sources of fracture origin [14], [17], [19], the fracture surface near origins i.e. at crack initiation and at crack propagation sites is usually smooth and then the surface becomes rougher as the original cracks increase in size. It can be noticed that this region contains of ratchet marks, these marks indicating multiple origins fatigue and the crack origin will be separated by ratchet marks and located approximately midway between the two marks (Fig. 4c). Also, there is no evidence of the so called “beach marks” or “progression marks”, such observation usually noticed with parts that operated continuously, or with only brief stoppages in service, and could be due to the friction of the two fracture surfaces of the crack against each other every cycle of the rotating part [19]. The final fracture surface shows a brittle cleavage failure with a rough texture, this region is known as the overload zone and its size indicates the magnitude of the load or stress when the final fracture occurs; in the studied case the final fracture zone is relatively small compared to the shaft cross-section indicating a high-cycle fatigue failure [14], [17]–[21].

IV. REPAIR PROCEDURE

Screw shaft is a critical twin-screw extruder component; therefore, failed shaft puts the extruder out of function.

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Replacing the broken shaft or perhaps the whole barrel section was not an optimal option due to sanctions on purchasing heavy industries equipment; also it bears a significant financial cost. Thus decision was taken to try to repair the excising failed screw shaft as presented in the following sections.

A. Welding Process

Welding was considered as a possible repair process since all necessary materials, equipment, and material testing were locally available which enables time and cost saving. The welding procedure included the following steps:

1) Cutting all fractured surfaces and affected zones uniformly till sound metals. This was done after adjusting to original positions by means of adjusting jig and control marks.
2) According to welding procedure and specification, the worn surfaces were beveled and buttered using electrode E-11018G.
3) Drilling of two threaded holes in both sections of the broken shaft with diameter of 70 mm and length of 100 mm.
4) Fabrication of threaded adaptor from the available alloy steel (AISI-9840); the chemical composition of the adapter material is given in table II.
5) Inserting the threaded adaptor into threaded holes and tightening as shown in Fig. 5, and then followed by buildup weld repair.
6) Application of the necessary nondestructive testing (NDT) such as, visual inspection (VI), dye penetrant testing (DPT), and magnetic particle testing (MPT) on all weld area.
7) Appropriate heat treatment was performed as explained in the following section.
8) Hardness test was performed before and after heat treatment procedure.
9) Finally, necessary machining of the repaired shaft and milling of the keyway slot was carried out.

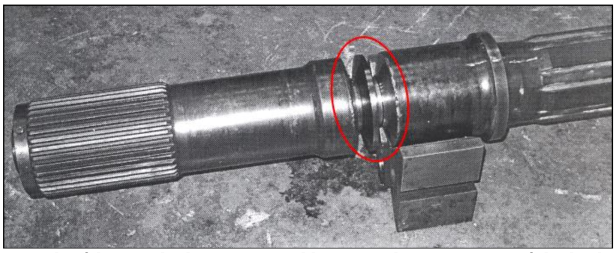

Fig. 5. The fabricated adapter inserted between the two pieces of the broken shaft

TABLE II: THE CHEMICAL COMPOSITION (WIGHT %) OF ADAPTER MATERIAL (AISI-9840) [15]

C	Si	Mn	P	S	Cr	Mo	Ni
0.38-0.43	0.20-0.35	0.7-0.9	0.04	0.04	0.7-0.9	0.2-0.3	0.85-1.15

B. Heat Treatment Procedure

The screw shaft is made of H13 medium-alloy steel that maintains high hardness and strength at elevated temperatures; therefore, to minimize the risk of cracking during welding process special procedures for heat treatment including adequate preheating and slow cooling are essential [15]. In this study the heat treatment procedure included pre-weld and post-weld heat treatment of the welded shaft.

As presented in Fig. 6, the pre-weld heat treatment procedure followed the below listed steps:

1) Preheating the shaft end with heating coil (shown in Fig. 7a) before welding at rate of 44 °C/h up to 590 °C.
2) After welding, the shaft is cooled under coil with rate of 43 °C/h up to 320 °C.
3) Remove heating coil and continue cooling the work piece using fiberglass blanket insulation (shown in Fig. 7b) with rate of 13.5 °C/h to temperature of 70 °C.

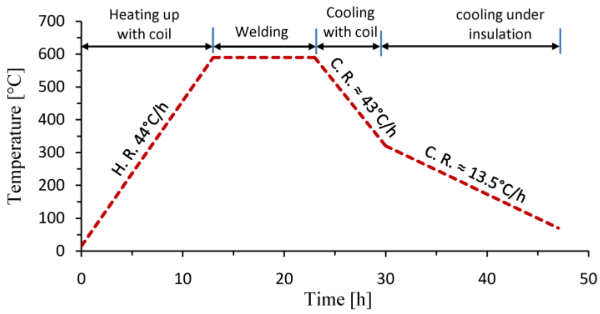

Fig. 6. Pre-weld heat treatment procedure

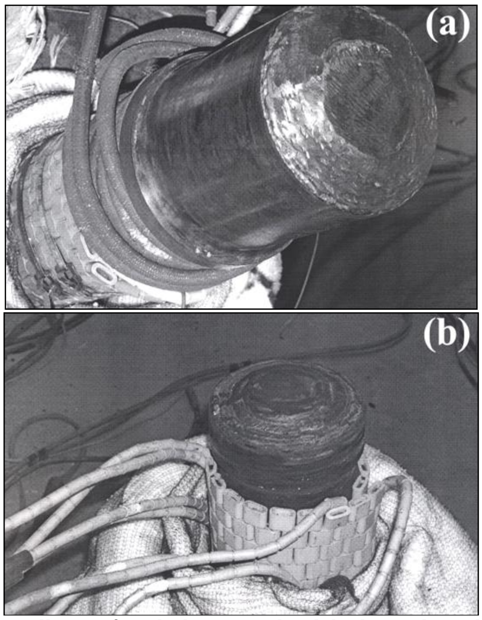

Fig. 7. Installation of (a) the heating coil and (b) the insulation blanket around the shaft

In order to reduce and redistribute the residual stresses those have been introduced during welding process, it is necessary to heat treat the welded shaft after welding is completed. Thus when the temperature reached 70 °C, the shaft subjected to a post-weld heat treatment procedure included the following steps which illustrated in Fig. 8:

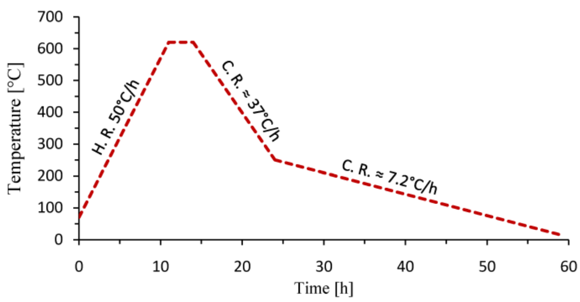

Fig. 8. Post-weld heat treatment procedure

1) Heating the work piece to 620 °C with heating rate 50 °C/h
2) Soaking the work piece at this temperature for 3 hours
3) Start cooling the work piece with cooling rate of 37 °C/h to 250 °C
4) Continue cooling the work piece with cooling rate 7.2 °C/h to room temperature.

V. Recommendations

In order to avoid similar accidents, the following precautionary measures and recommendations are proposed:

1) Ultrasonic testing has to be performed on unbroken shaft in order to check the condition for any cracks by means of compression probe.
2) Schedule the lubrication of motor, bearings, and packing gland as indicated in maintenance and operation manual.
3) Measure and/or photograph screw elements when pulled out, at least every 1500 hours of operation in order to monitor the wearing rate.
4) Monitor vibration level in both extruders which will indicate the amount of wearing in screw elements and barrels.
5) Replace and/or weld repair on wearing and grooving in screw elements and barrels.
6) Regular check the alignment of all extruder components, especially at coupling between the motor and gear box, and between the gear box and the screw shaft, since misalignment causes cycle bending stress that leads to fatigue failure [16], [22].
7) Regular check the clearance between the two screws and between the screws and the barrel and ensure that they are within the design limits.
8) During the maintenance or when dismantling the extruder for regular inspections the sites that considered as stress raisers such as, steps at changes in diameter, holes, abrupt corners, keyways, splines, grooves, threads, …etc. have to be checked carefully.
9) Avoid operating extruders or similar equipment when abnormal level of vibration or noise is detected, instead inspections have to be performed.
10) Since the extruder unit is controlled with Discrete Control System (DCS), it is advisable to modify the system trends in order to record any vibration noise that indicates wearing in the system.
11) The manufacturer Coperion GmbH presented a new wear diagnosis system “COBRA LG”. With this system, information on the actual state of wear of the inner walls of barrels can be obtain rapidly without dismantle the extruder barrels [23].

VI. Conclusion

The case of the failure of one screw shaft of a twin-screw extruder was investigated. By means of the preliminary analyses of the fracture surfaces and by analyzing all relevant data it was possible to determine that the combination of cyclic torsion and bending loads is the cause of the failure. The failure was determined to be low stress, high cycle fatigue. Fatigue cracks initiated at the keyway root and propagated under a cyclic stresses causing the failure. A successful repair procedure based on welding technique was implemented. Inspections and measurements carried out on the repaired shaft and on the extruder underline that the applied solution method is appropriate. Finally, the study proposed precautionary measures and recommendations that help to avoid similar failures and familiarize operations personnel to the common causes of extruder screw shaft failure.

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